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EXTREMELY HIGH LATITUDE AURORAS. PART I.(U)

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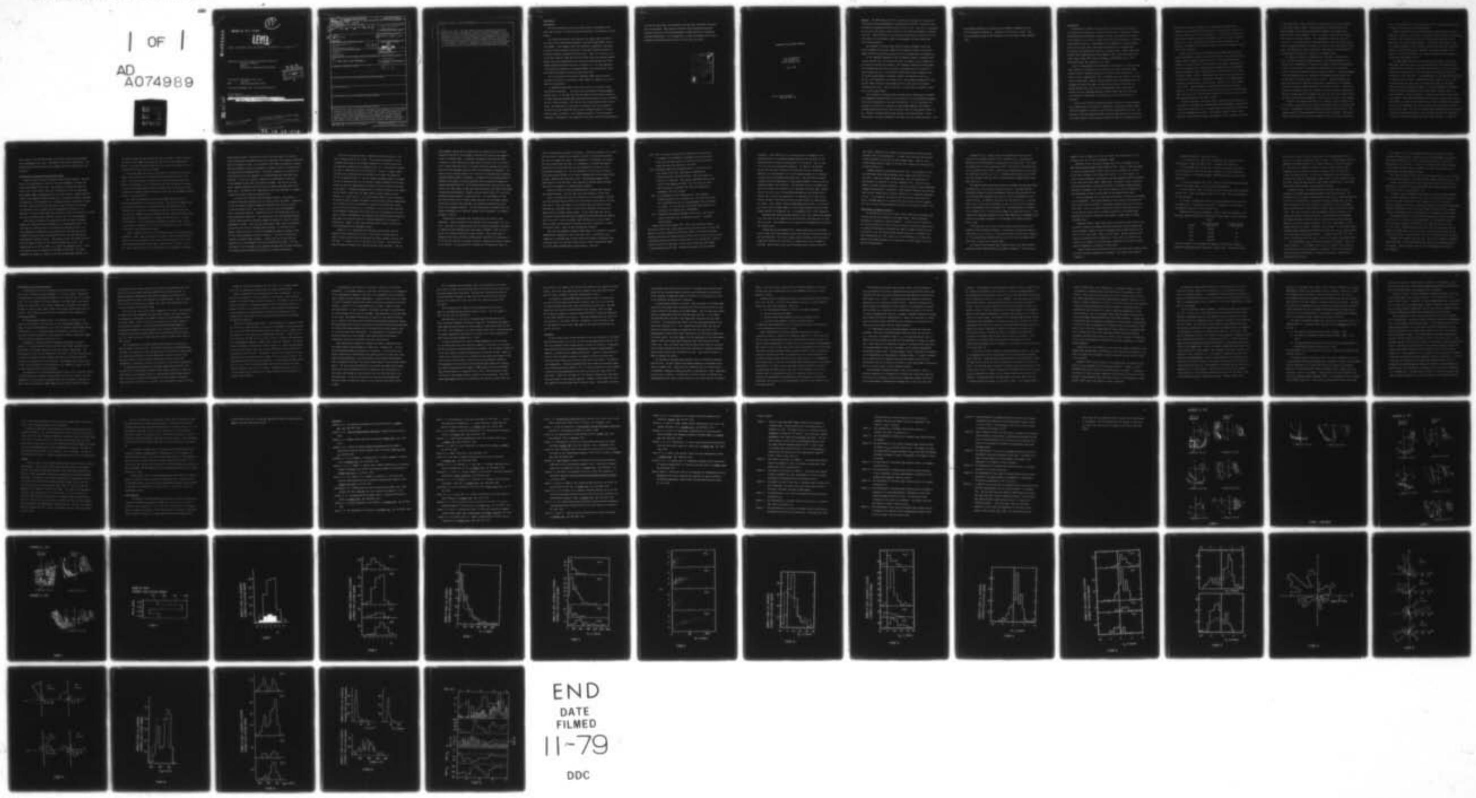

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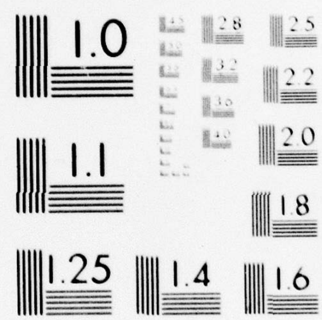

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The work under this contract had as its goal the time-dependent phenomenological modeling of the polar cap regions. The vehicle for modeling the caps has been to analyze the following collection of data: DMSP images showing polar cap auroras; DMSP electron measurements; hourly averages of the interplanetary magnetic field; ground magnetometer data from Thule; and magnetic indices. DMSP images from the winters of 1972-1973 and 1974-1975 provided consistently good records of the northern polar cap region and were used as the primary

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basis of the study. The DMSP images for these periods were traced and gridded in corrected geomagnetic coordinates and local geomagnetic time. The subset of cases for which auroras occur at above 80 degrees corrected geomagnetic latitude was identified and further categorized by local time interval of occurrence (morning, midnight, evening sectors). The occurrence of extremely high latitude aurora in each category was correlated with magnetic indices, magnetometer response at Thule, and solar wind parameters. The correlation of cap size as determined by poleward auroral boundaries, and the time variation of these with the above parameters was also made.

Final Report

Introduction

The work presented here has as its goal studies of phenomena in the polar caps in order to initiate theoretical modeling of the dynamics of these regions.

The initial data used in this study are the images taken from 1972 to the present by the Defense Meteorological Satellite Program (DMSP, earlier called DAPP). These images reveal the occurrence, orientation, and extent of auroral forms from the auroral oval to very high latitudes, giving, on occasion, excellent coverage of the polar caps. Times of occurence of arcs in the polar caps are times when the cap is most active and indicate magnetospheric-solar wind interactions that involve the high latitude tail lobes, regions normally protected from such. Therefore, it is of some importance to determine the conditions, both magnetospheric and interplanetary, under which major involvement of the polar caps takes place.

The first portion of this report "Extremely High Latitude Auroras" contains the results of the survey of DMSP images, and appears in a form to submit for publication.

In completing this phase of the study a variety of questions arose, particularly concerning the polar caps during times of extreme magnetospheric quiet. At the same time data from improved electrostatic analyzers on board currently operating DMSP satellites and planned for future satellites as well, became available. The data are in 16 energy channels and are very clean. The importance of these data for studies of the cap is apparent. To facilitate such studies the data are now routinely reduced to a format which is easily accessible. The calibration results of the electrostatic analyzers, a discussion of the reduction of the data, and initial observations

of polar cap and auroral oval boundaries from the data, constitute the second part of the report. This section is entitled "The Precipitating Electron Detectors (SSJ/3) for the Block 5D/Flights 2-5 DMSP Satellites: Calibration and Data Presentation." It is prepared for circulation through the Air Force Geophysics Laboratories where the data are processed and stored.

EXTREMELY HIGH LATITUDE AURORAS

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July, 1979

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Abstract The DMSP images from 1972 to present were surveyed for auroral arcs occurring at corrected geomagnetic latitude greater than 80^{o}. Auroras at these latitudes are designated extremely high latitude auroras. They can be categorized by the local time sectors in which they occur and their relationship to discrete oval arcs. Nearly 300 cases of cap auroras from the Winters 1972-73 and 1974-75 are selected for correlation studies with geomagnetic activity indices and solar wind parameters.

One category of extremely high latitude auroras, midnight sector oval auoras expanding into the cap, appears to be substorm related, occurring for higher values of K_p, AE and D_{st} than the rest, and, generally, for negative B_z.

Of the remaining categories by far the greatest number of extremely high latitude auroras occur in the morning sector, and appear to be an expansion of the system of morning arcs poleward. The remaining categories include evening arcs expanding into the cap, and single, sun-aligned arcs, more familiarly called 'polar cap arcs.' The auroras in these three latter categories occur for similar magnetospheric conditions, namely, for moderate values of K_p and D_{st}, but comparatively low values of AE. The single sun-aligned arcs occur for the lowest activites, the morning arcs for a wide range of conditions including active ones. Little cap activity is found when all magnetic indices are at their lowest values.

The occurrence of extremely high latitude auroras (excluding the midnight oval expansions) depends strongly on the direction of the interplanetary magnetic field and the magnitude of the solar wind velocity. By far the greatest percentage of cases occur for positive B_z (solar-magnetospheric coordinates), although morning auroras are found in the cap even for large negative values of B_z. Further, extremely high latitude auroras occur preferentially in local time sectors of the cap according to the value of B_y (B_z assumed positive). They

have greater frequency of occurrence in the morning for negative B_y, and in the evening for positive B_y. (Single arcs occur for $B_z > |B_y|$). This is in the opposite sense of the increases in the cap electric field (Heppner, 1972).

Introduction

Observations of auroral arcs in the polar regions have been reported in the literature for many years. Often the reports were of individual sightings, fortuitously made from ground, airplane or rocket, and limited by the motion of the observer, or the arcs, or both, and also by the infrequency of occurrence and lifetime of the arcs. Nevertheless, in the composite of auroral studies polar cap arcs have come to mean weak, sun-aligned arcs occurring within the auroral oval during quiet times and occurring rarely. [Davis, 1960, 1962; Denholm, 1961; Denholm and Bond 1961; Akasofu, 1963, 1968, 1972; Gustaffson, 1967; Lassen, 1968, 1972; Eather and Akasofu, 1969; Whalen et al., 1971; Romick and Brown, 1971; Akasofu et al., 1972]

There is disagreement on the lifetimes of polar cap arcs. They are sometimes referred to as short-lived, but have been recorded in all-sky camera pictures taken at 1-minute intervals as lasting for more than an hour. (J. A. Whalen, private communication, 1977) In addition, they are found to occur more often in the morning. However, in the morning sector, sun-alignment and oval alignment are nearly the same, as pointed out by Lassen (1973), and it is unclear whether polar cap arcs are distinguishable from a collection of morning oval arcs expanding poleward. Akasofu (1968) and Pike (1975) show the occurrence of these arcs as characteristic of the recovery phase of substorms.

In one of the earliest statistical studies of auroras at high latitudes, Davis (1963) found the occurrence of morning arcs observed from Thule (86.8^{o} corrected geomagnetic latitude) to anticorrelate with magnetic activity. More recently, Lassen and Danielsen (1978) constructed mass plots of arcs recorded by all-sky cameras at high latitude stations for times of no substorm activity.

They ordered the plots according to the interplanetary magnetic field components to show contraction of the auroral oval and greater definition of a polar cap system of arcs with increasing B_z. The polar cap arc system is, however, quite clearly present in the morning for all but the most negative values of B_z. Thus, ground-based observations show an asymmetric, but systematic involvement of the polar cap which is related to magnetic activity and the IMF z-component.

Imaging devices on the polar orbiting Isis and DMSP satellites have greatly increased the extent of polar cap and auroral zone coverage and have prompted several studies of polar cap arcs. Focus has been on the most dramatic of auroras in high latitude regions: the single, well-defined arc directly crossing the cap, passing near the magnetic pole and sun-aligned. Excellent examples of these, obtained from the DMSP satellites, are shown by Meng and Akasofu (1976). Studies made from the Isis data show such arcs occurring for interplanetary conditions of northward B_z and magnetospheric conditions in which AE has a local minimum. (Berkey et al., 1976; Ismail et al., 1977). These findings are consistent with ground observations. Ismail et al. (1977) also point out that while the occurrence of sun-aligned polar cap arcs is low, they have been observed on successive passes, possibly indicating persistence on the order of hours.

The work presented in this paper takes a somewhat different approach to the problem of specifying the interplanetary and magnetospheric conditions for which polar cap auroras occur. It begins with the recognition that the polar cap is not unambiguously defined. The ambiguity exists in theory and in practice. Theoretically the polar cap boundary is the transition from closed

to open field lines. Such a transition is clearly made only in the simplest of open magnetospheric models: the vacuum model for which merging of the Earth's magnetic field and the interplanetary magnetic field takes place where the two are anti-parallel. (See, for example, Stern, 1973 and Crooker, 1979, and the references therein). The transition actually does not exist at all for a truly closed model of the magnetosphere, since the dipolar field lines are simply distorted, not broken, by a viscous interaction with the solar wind. Nevertheless, for high latitudes the field lines are stretched back so severely that the question of closing is, if anything, moot.

In practice a variety of transitions has been used to delineate the caps: the 40 keV electron trapping boundary, the poleward boundary of the auroral oval as determined by a significant decrease in electron precipitation or the last discrete arc, the position of the reversal of the convection electric field, the poleward boundary of Birkeland currents. These measurements of the cap boundaries are not necessarily in agreement with each other, nor are they able to be clearly made on all occasions. Generally speaking, the polar caps have come to mean the regions where, compared to the surrounding auroral oval regions, measured quantities are uniform and small. Auroral arcs in the caps indicate by their own occurrence and by the particle precipitation and field changes that must accompany them, that the caps are no longer uniform and quiet, particularly in comparison to a quiet oval, if such is also present.

Therefore, the approach taken here is to study all types of auroras that occur within a region that can be clearly specified and that, at the same time, has good correspondence to what is generally accepted as the polar cap. The region above 80^{o} corrected geomagnetic latitude (CG) is studied. The auroral forms in this region are classified primarily by the local times in which they

occur. The occurrence of the extremely high latitude auroras are then related to magnetic indices and solar wind parameters.

Images from satellites in the Defense Meteorological Satellite Program (DMSP) are the basis of the study. The Program routinely places sun-synchronous satellites into circular polar orbits at altitudes ~800 km either in the dawn-dusk or the noon-midnight meridians. The auroral images made by means of scanning radiometers are now familiar research tools and their properties have been extensively discussed. [Akasofu, 1974; Pike and Whalen, 1974; Rogers, et al., 1974; Snyder, et al., 1974; Carovillano, 1975; Sheehan and Carovillano, 1978; Eather, 1979.]

The DMSP images from 1972 to the present were surveyed. The group of DMSP images that were found to be most appropriate for the study were those obtained during the winters of 1972-1973 and 1974-1975. For the two winters chosen, good coverage of the polar cap region was consistently obtained in the images of both satellites: the noon-midnight; and the dawn-dusk satellites. In addition, good coverage in supporting data was available. Only northern hemisphere images are used since city lights which appear in the images greatly facilitate gridding the images in corrected geomagnetic coordinates (CG) and in corrected geomagnetic local time (CGLT), (Whalen, 1970). To make as complete a study as possible all images for the winter months chosen were gridded. This permitted designation of the class of auroras that occur above 80°CG. A member of this class will be called an extremely high latitude aurora to avoid confusion with the way in which the term 'polar cap aurora' has come to be used. The class of extremely high latitude auroras will include the polar cap auroras discussed in the literature only when they reach 80°CG. It does not exclude any auroras that reach these latitudes. It should be

noted, however, that the DMSP images in this study rarely show the dayside cap (in geomagnetic local time: from 0800 to 1600 hours through noon). Thus, extremely high latitude auroras in the midday sector are excluded from the discussion.

Categorization of Extremely High Latitude Auroras

Figures 1-3 show a variety of extremely high latitude auroras. Shown are traces of the DMSP images on grids of corrected geomagnetic latitudes and corrected geomagnetic local time. The procedure of tracing was chosen to better focus on the shape, length and distribution of arcs by eliminating gain changes, light streaking and other obscuring intensity changes which are common to the images and their reproduction. An attempt was made to reproduce the intensity of the individual arc or diffuse aurora by the density of cross-hatching. While the traces are from actual passes (listed for each trace) it is probably best to consider them as representative cartoons of the originals. The traced DMSP images are displayed to show the structure of the arcs that reach latitudes greater than 80°, and are felt to be representative.

Each group of selections is identified by date and satellite number: #9532 is in a dawn-dusk orbit and #8531 is in a noon-midnight orbit. For each image the universal time of the equatorward crossing is given. For these examples the satellites were descending from the north pole at the universal time given; thus, the universal time for the polar crossing is approximately 25 minutes earlier. Also given is Kp for the 3-hour period in which the image was made and the one-hour averaged value of AE. The dashed lines are at 70° and 80°CG. An x marks the geomagnetic pole. Lines are drawn from noon to midnight and from 0600 to 1800 CGLT. For easier comparison all images are rotated so that the noon-midnight meridian is in

the same direction, with noon toward the top of the page. In most instances the limits of the image are apparent and they have not been additionally marked. Areas that are light-struck have been outlined and usually occur for Satellite #31 in the center of the image.

Within each Figure the traces are arranged in chronological order with images from Satellite #31 in the left hand row and those from #32 in the right. With the exception of Figure 3c, the satellite passes within each Figure are successive. The two satellites cross the cap within 4-11 minutes of each other giving together a fairly extensive view of the cap and a time resolution of changes in auroral structures finer than the 100 minutes between passes of a given satellite.

The rapid scan radiometer that forms the DMSP images scans in the direction perpendicular to the satellite path. Arcs that are aligned in the scan direction have better resolution than those perpendicular to the scan direction if there is considerable arc motion. Thus, Satellite #31 will show arcs aligned along the midnight oval more sharply than those along the dawn sector. The situation is reversed for Satellite #32. It takes 10-20 minutes to form a single image (depending on extent); thus, a sense of the motion or stability of the arcs can be obtained from their resolution differences in the two satellite images.

Figure 1 shows a series of four consecutive passes for each satellite on November 17, 1974. The four passes occur within a time interval that falls between two fairly extended, active times as measured by AE. Prior to and following these passes AE exceeds 400γ. The first set of passes, 1a and 1a', shows a fairly active oval for which there are no examples of extremely

high latitude auroras. The series of arcs in the dawn sector is much more clearly defined when scanning along the arcs (Satellite #32) implying considerable motion or weakness or both. In the Satellite #31 image the morning arc system, with the exception of the most poleward arc, appears diffuse or unresolved and continuous with the midnight sector. The better resolution of Satellite #32 shows multiple short arcs imbedded in a diffuse background (less dense cross hatching). It does not, however, indicate the relationship of these arcs to the midnight sector which lies outside the image. The arcs in the dusk sector (shown by satellite #32 only) are more intense and longer than in the dawn sector. The width of the "instantaneous oval" near 1800 CGLT is uncharacteristically large for this and the next pass.

In the next set of passes, shown in Figures 1b and 1b', the system of morning arcs has moved poleward into the region greater than 80^{o}CG. Comparison of the two satellite images at 0600 CGLT indicates considerable stability in the most poleward arcs, there being a near one to one correspondence after a ten minute interval. Satellite #31, for its scanning direction, has good resolution of these arcs. The evening arcs, too, have expanded poleward and have become much more obliquely aligned in relation to lines of constant geomagnetic latitude. They are also considerably weaker than in the previous pass, and do not reach to extremely high latitudes. In the third set of passes, Figures 1c and 1c', the hourly averaged AE reaches a minimum of 036γ for the period spanned by the whole of Figure 1. The set of morning arcs remains at extremely high latitudes. A short, thin arc is seen near the magnetic pole in the midnight sector in the Satellite #32 image. (It does not appear in the #31 image, but is possibly obscured there by light streaking.) The evening sector has faded away except for two small patchy areas.

The last set of passes shows a dramatically altered situation. The hourly average value for AE is 218γ. The evening arcs reappear in their customary narrow band at the poleward boundary of the diffuse aurora and are apparently continuous with midnight sector arcs. The system of morning arcs has, at 0600 CGLT fallen to below 80° CG. However, a single, highly structured arc continuous with the midnight oval becomes sun-aligned by 75° CG and extends to 85° CG. The arc remains remarkably stable in position for the 11 minutes between the two satellite images although the very tight swirls for the first image appear less distinct and more loosely structured in the second. A slight morningward drift is apparent between the two images. The arc shown in these last two images would no doubt qualify by every standard, as a polar cap arc. It is interesting, however, that as measured by AE (Kp is nearly constant throughout the four passes) and more importantly, by the condition of the surrounding oval aurora, the well-defined, single arc occurs not when activity is at a minimum, or even on the declining side, as the minimum is approached, but rather prior to the resumption of activity. Here, at least, involvement of the extremely high latitude regions during the most quiet time occurs by means of a poleward expansion of the system of morning arcs. Figure 1, then, shows extremely high latitude auroral arcs in the morning and in the midnight sectors.

Figures 2a - 2c' demonstrate that extremely high latitude arcs can develop in the evening sector as well. The sequence of passes shown in Figure 2 begins after 12 hours during which the hourly average of AE was less than 100γ. It rises to 103γ for the first set of passes. Both satellites show the system of morning arcs reaching extremely high latitudes. There is

good agreement between the two images with the exception of an arc shown between 85° and 90° CG in the image of Satellite #31, which is not apparent in that of Satellite #32. In addition, the image of Satellite #32 shows evening arcs, long, coherent and widely spaced reaching to 85° CG. The next set of passes, Figures 2b and 2b', for which the hourly average of AE falls to 048γ, shows less agreement which may indicate considerable arc movement. The morning and the evening systems of arcs are still at extremely high latitudes, although somewhat weaker in intensity. In Figure 2b arcs continuous with the midnight sector appear to detach themselves and move poleward becoming sun-aligned between 80° and 85°. By the time Satellite #32 records the arcs some minutes later they appear to have been swept dusk-wards, and remain sun-aligned at extremely high latitudes. Finally, one pass later, Figure 2c', the entire midnight-evening quadrant is filled with arcs. The relationship of these arcs with the oval arcs is various being continuous in the evening, oblique but perhaps continuous near midnight, and apparently detached from either sector at the highest latitudes. For all three passes of Satellite #32, the system of morning arcs at 0600 CGLT remains fairly stationary, its poleward boundary at ~82° CG.

Another kind of extremely high latitude aurora was found to occur frequently. These are auroras in the midnight sector that appear to be oval arcs: they tend to be aligned along lines of constant geomagnetic latitudes, as opposed to those midnight sector arcs shown in Figures 1d and 1d', and 2b and 2b' that become sun-aligned at high latitudes. This second kind of midnight sector aurora reaches latitudes greater than 80° by an expansion of the entire oval poleward, as during a substorm. Examples are shown in Figures 3a, 3a' and 3b'. For the first set of passes the two satellites differ in

times of equatorward crossings by 26 minutes. The hourly average of AE is 342γ, and this value is typical of the magnetic activity for several hours before and after the images were taken. The expansion of the midnight oval extends into the morning sector and thus it is impossible to visually distinguish between the oval aurora and what has been designated, in Figures 1 and 2, the system of morning arcs. For the thickness of the oval and the value of AE the equatorward boundary of the oval at midnight and in the evening sector is high. (Sheehan and Carovillano, 1978) Interplanetary magnetic field measurements at this time show a weak negative B_z turning weakly northward. This may be an example of a contracted-oval substorm.

Figure 3b' gives one other representation of extremely high latitude oval aligned auroras. For this case, the hourly average of AE was 796γ.

Figures 1-3 reveal why polar cap auroras are so poorly defined. Auroras can reach extremely high latitudes in a wide variety of ways and in all local time sectors. They can appear to be continuous with oval aurora at lower latitudes and "attached" there; or they can be "attached" to the oval but emerge from it at large, oblique angles. On the other hand, they can be "detached" from the oval arcs and not apparently associated with any specific part of the oval. Arcs at extremely high latitudes can be long or short, weak or bright, structureless as the quiet oval arcs or made up of a series of distinct swirls. They can have considerable lifetimes.

Even with the extended coverage of DMSP images it is difficult to specify unambiguously categories of arcs in the polar caps. Nevertheless, four categories of extremely high latitude auroras are defined, principally indicating the portion of the cap in which they are found, although each seems to possess other distinguishing characteristics. They are:

P(1): One or two long, individual arcs appearing or actually seen to originate (or terminate?) in midnight sector oval auroras. These arcs can range from very faint with little structure to bright and sharp and interiorly convoluted.

P(2): Extremely high latitude morning auroras. The discrete arcs that appear in the local time range of 0400-0900 are characteristically fine and multiple. Their orientation is difficult to establish. They appear sun-aligned, but the oval itself is sun-aligned near 0600. When this array of short weak arcs moves to latitudes $\gtrsim 80^{o}$ they are identified as belonging to the P(2) category.

P(3): Arcs principally in the evening sector. This category includes patches and arc fragments that can extend across the cap to morning hours, but are distinguishable from the morning arc system. It also includes well defined high latitude arcs attached to the evening sector (1600-2000).

P(4): Extremely high latitude midnight oval auroras. This type of aurora occurs when the oval expands poleward to extremely high latitudes.

Morning auroras and Category P(2): While the evening and morning statistical ovals do not differ greatly from each other except for very high magnetic activities (Feldstein and Starkov, 1967), the actually occurring morning auroras and the precipitating electrons that are their source are often distributed through far greater latitudes than on the evening side. (Verification of this can be made with a brief survey of dawn-dusk DMSP images or precipitating particle data. Quantitative support will be presented

elsewhere). This difference can be reconciled with the symmetry of the statistical oval if the average boundary positions are the same, but the deviation from the average is much greater in the morning. This is found to be the case for the poleward boundaries. In addition, the morning auroral arcs have more structure and variability than the evening arcs. Generally, the "instantaneous oval" in the morning appears as a collection of short, thin arcs branching from larger ones. The collection can appear continuous from the equatorward to the poleward boundary. There can also be significant gaps in the collection. The gaps may occur in the images only: auroral arcs below the threshold of the radiometer could fill them. Whether this is the case or not, the resulting configuration, particularly with a limited view, can give the impression of an individual arc or arcs in the central cap when in fact what is seen is an upper bound of a gappy morning arc system. Thus, without having corresponding particle data, or coverage of the entire cap in a single image, it is not always possible to make an unambiguous decision to categorize arcs as belonging to P(1) or P(2) categories.

Extremely high latitude morning auroras, P(2), then, appear most commonly to be the result of the expansion of the collection of morning oval arcs into the cap regime. This expansion can be continuous to the magnetic pole and into the evening sector.

Evening auroras and Category P(3): High latitude arcs in the evening sector (~1800 local time) generally differ from those of the morning sector in the following ways: the arcs are longer, more continuous; they can be quite bright and coherent; the collection of evening arcs is more confined in latitude. When evening aurora reach latitudes around or greater than 80^{o},

they seem to emerge from the dayside and approach high latitudes much more obliquely than in the morning side. In these cases, the cap region between the most poleward arc and the oval often appears empty. From the survey of DMSP images such arcs appear to be much less frequent than extremely high latitude morning arcs.

Midnight auroras and Categories P(1) and P(4): The appearance of arcs in the extremely high latitude midnight sector seems easily divisible into two types: those arcs aligned along the oval, P(4); and those that are discontinuous in direction to the oval alignment, P(1). The latter occur singly or at most in pairs or triplets. They can be weak or have considerable strength and definition; in addition to their dramatic departure from the oval they can have a great deal of structure (swirls, etc.) or give the appearance of none. It is primarily this type of arc that has been called polar cap aurora, although again it is cautioned that the weak arcs in this category, P(1), may be quite indistinguishable from those in the morning category, P(2).

Relationship to Magnetic Activity

For the Winters of 1972-73 and 1974-5 nearly 300 cases of extremely high latitude auroras were identified in the DMSP images. Their distribution according to P-category is shown in Figure 4. In only the very crudest way can this distribution be taken to indicate relative occurrence frequency since no attempt has been made to determine the number of images in which it would be possible to see the extremely high latitude auroras or to otherwise sort their distribution (as to UT, season, etc.) Nevertheless, it is clear that auroras most commonly pervade the extremely high latitude regions of the cap from the morning sector.

Dependence on K_p: Figure 5 shows the distribution of all cases of auroral arcs at greater than 80^o CG as a function of K_p. Each image was identified with the appropriate pre-existing 3 hour K_p interval. The shaded area shows cases for arcs occurring at $\geq 85^o$. The center of the distribution is at K_p values between 3 and 4, certainly not representative of quiet times. Very few cases occur for $K_p = 0$ or 1. Extremely high latitude arcs at $\geq 85^o$ occur for slightly lower K_p, since the distribution is symmetrically distributed about $K_p = 3$.

The high latitude auroras were sorted by P-category and then distributed according to K_p. The results are shown in Figure 6. The high latitude morning and evening arcs have approximately the same characteristics as the total distribution, peaking at K_p values of 3 and 4, and showing very few cases at low K_p. In addition, they show very few cases for $K_p > 4$, and the high K_p tail of the total distribution is seen to derive from the midnight sector high latitude arcs in category P(4). The distribution for category P(4) is peaked at $K_p = 4$ and occurs for higher K_p values than the rest. This confirms the impression obtained from the DMSP images that the midnight sector auroras are northward expansions of the midnight oval during relatively active times.

The single P(1) arcs occur at lower values of K_p than the rest, the maximum in the distribution being $K_p = 2$ (although a considerable number of cases exist for $K_p = 3$ and 4). It is the occurrence of this type of auroral arc at extremely high latitudes that has led to the often expressed belief that polar cap arcs occur in quiet times.

We conclude that extremely high latitude auroras occur when worldwide magnetic activity (indicated by the K_p index) is moderate. The activity is

somewhat less for single arcs across the central cap, and greater for oval expansion into the cap from the midnight region.

Dependence on AE: The hourly average value of AE is assigned to each DMSP image showing extremely high latitude auroras. Figure 7 shows the number of cases of extremely high latitude auroras in all categories as a function of the hourly average of AE in bins of 50γ width. (1γ = 10^{-5} gauss.) In order to better appreciate the meaning of the distribution we have also plotted in the same Figure (the weaker, dashed line), the number of hours a given AE value prevailed during a representative month in the Winter months surveyed. The month is November, 1974. The scale for number of hours in November has been normalized so that the areas under the two graphs are the same.

With the exception of the lowest bin of AE values: from 0-50γ, the graphs are not dissimilar. The relative absence of cases for AE in the lowest bin must be dealt with in relation to the particle precipitation over the cap at such times. That is, we cannot conclude that there is less particle access to the caps for low AE since the general intensity of all precipitating particles may itself be lessened to the extent of being unable to produce detectable arcs.

Otherwise, Figure 7 shows that there are consistently fewer cases of cap auroras for values of AE greater than 500γ than hours in which these values occur; although a number of cases of extremely high latitude auroras do, in fact, occur in this range: about 7% of the total. Further, there are more cases of cap auroras in the 50-400γ bins. Thus, there is a trend for cap auroras of all kinds to occur with greater frequency at the lower AE values than the frequency of occurrence of such values.

Figure 8 shows the distribution of cases of extremely high latitude auroras for 50γ AE bins when separated by P-category. The scales are the same as in Figure 7.

Comparing categories it can be seen that:

a) All cases for AE > 500γ occur in categories P(2) and P(4) with by far the greater number occuring for P(4): midnight oval expansions.

b) The midnight oval auroras, P(4), are much more broadly distributed over variations in AE than are the other categories; the peak distribution for this category is considerably higher (300-400γ) than for the other three categories.

c) The three categories P(1), P(2), and P(3) have distributions with peak values in the 0-150γ range, as does the total distribution.

d) P(1) and P(3) occur, on the whole at less active times than the morning auroras, P(2). These are primarily times of AE < 250γ. The two distributions are not dissimilar.

e) For P(1) a significant portion of the distribution (~27%) occurs for AE between 0-50γ. The reverse is also true: the majority of cap auroras at the lowest AE values fall within category P(1).

Comparison of AE and K_p dependences: Table 1 shows the comparison of the AE and K_p values for which the distribution of cases peaks in each P-category:

Table I

Category	AE Spread for Peak Distribution	K_p Spread for Peak Distribution
P(1)	00-100	2
P(2)	50-150	3-4
P(3)	50-100	3-4
P(4)	300-400	4

With the exception of the midnight oval auroras, P(4), the most common K_p values are relatively high in comparison to those of AE. To show this trend

more precisely, plots of the K_p value against the corresponding AE value for each case in a given category are shown in Figure 9. The distribution for P(4): midnight oval expansion shows a very regular increase of K_p with increasing AE: the increase in magnetic activity over mid to upper latitude ranges (indicated by K_p) is directly related to increased auroral or electrojet activity as indicated by AE. For the other categories, and particularly for categories P(1) and P(3) comparatively large values of K_p are reached for small AE values, indicating that extremely high latitude auroras tend to occur while mid-latitude current systems control magnetic activity.

Dependence on D_{st}: The appropriate hourly average value of D_{st} was assigned to each DMSP image showing extremely high latitude auroras. The distribution for all cases of high latitude auroras in D_{st} is shown in Figure 10. As for AE, the distribution of occurrence of hourly averages of D_{st} for the month of November, 1974, and normalized to the number of cases of extremely high latitude auroras is also plotted for better comparison (the thin, dashed line.) The scale is chosen so that the magnetic activity increases to the right, and the data is sorted in 10γ bins. The distribution for November, 1974 shows that most of the time during a typical winter month the magnetosphere is in a storm recovery situation: there are a large number of cases between +10 and -20γ (~60%): relatively low D_{st} values. For the whole class of extremely high latitude auroras 60-70% of the cases occur for D_{st} values shifted 10γ toward higher ring current activity: to between 0 and -30γ. Very few cases of cap auroras occur for $D_{st}>0$: that is, for lowest ring current values.

The distributions in D_{st} are sorted according to P-category. These are shown in Figure 11. The midnight oval auroras, of category P(4) continue to be associated with the higher magnetic activities of the total distribution and the peak of the distribution is between -10 and -30γ. There are very few cases (3%) for $D_{st}>0$.

The absence of cases of extremely high latitude auroras for the most commonly occurring D_{st} bin: between 0-10γ is strongly dependent on P-category. The evening cap auroras, P(3), have a distribution over D_{st} much like the distribution of D_{st} in time. It is the only category with a large percentage of cases when the ring current is weakest. The small sample does not allow interpretation for high magnetic activity.

The single cap arcs in P(1) have the next greatest number of cases occurring at low ring current values. There are for this category no cases for $D_{st} < -40\gamma$.

Finally, the morning aurora, P(2) (like auroras in P(4)), have very small frequency of occurrence for D_{st} positive (5%); peak strongly between -10 and -20γ; and can occur for D_{st} values of -70γ.

In summary, the two categories that appear to have the greatest similarities in their dependence on magnetic activity are the single arcs across the cap, P(1); and the evening arcs. They commonly occur for low electrojet activity (taking AE as measure); moderate K_p interpreted as moderate mid-latitude activity for AE small); and do not occur during storm times but are otherwise relatively independent of D_{st} in the moderate to low magnetic activity ranges.

The morning auroras at extremely high latitudes also occur at relatively low AE values for the value of K_p, although both are distributed at higher values than for categories P(1) and P(3). The common K_p values are from 3-4; AE, 50-150. Morning auroras do not occur often for the lowest and most commonly occurring values of D_{st}; but have a strong distribution peak for D_{st} between -10 and -20γ. Morning auroras can occur for relatively large D_{st} values.

Midnight oval expansions into the cap: P(4) occur for magnetic conditions during substorms: AE and K_p moderately high, D_{st} values showing appreciable ring current. They very rarely occur for the lowest magnetic activities in all categories.

Relationship to Solar Wind Conditions

A distribution of cases of extremely high latitude auroras was made for each of the following solar wind parameters: velocity, density, temperature, the magnitude of the interplanetary magnetic field (IMF) and each of its components. For all parameters the value assigned to the DMSP image is the hourly average (or occasionally, for velocity, temperature and density, three-hourly average) as listed in King (1977), taken in the hourly interval before the arc occurred. The coordinate system used for the magnetic field components is solar-magnetospheric.

The interplanetary magnetic field: The occurrence of auroras in the polar cap is sensitive to the direction of the interplanetary magnetic field. Figure 12 shows the distribution of all cases of extremely high latitude auroras according to B_z. It is peaked strongly for positive B_z, between 2 and 3γ. The spread in the distribution is quite large, there being a significant number (26%) of cases for negative values of B_z to -7γ.

A breakdown of the distribution according to P-category is shown in Figure 13. The distributions for P(1) and P(3) shift toward positive B_z with 91% and 84% of the cases occurring for positive values, respectively. The distribution in P(2), for the morning arcs, has many of the same characteristics of the total distribution with somewhat fewer cases occurring for negative B_z (82% of the cases occur for B_z positive). The midnight oval auroras, those in P(4), are responsible for a good portion of the negative B_z cases; only 30% of these auroras occur for positive values.

The component of the interplanetary magnetic field in the z-direction varies in direction over much smaller time intervals, on the order of hours, than the components in x and y which are dominated by sector structures, perduring for days. Thus, in the survey of DMSP images over two winter periods it could be

anticipated that near equal cases for B_z positive and B_z negative would occur, the scale of the variation being much smaller than the time surveyed. In addition there are large gaps in interplanetary magnetic field data as the measuring satellite enters and remains in the magnetosphere. This too, should have no effect in biasing the B_z sample, since again, the missing data occurs for time intervals on the order of days.

Such is not the case for the x and y components of the IMF. The variations in direction of these components are on the same order as the time intervals of missing data, and further, the number of sectors in the six months surveyed is, itself, small. Thus, a bias in the available data for either toward or away sectors can develop. For the two winters when both DMSP images and interplanetary magnetic field measurements were available roughly 64% of the surveyable data occurred during toward sectors (as determined by the sign of B_x). Or, there are twice as many surveyable images in toward sectors than in away sectors.

The distributions of extremely high latitude auroras in B_x and B_y are shown in Figure 14 (solid lines). The dashed line shows the distribution when the number of toward sector cases are given half the weight of the away sectors. The resulting distribution has only slightly more cases of extremely high latitude auroras occurring in toward sectors than in away sectors (53% altogether); a difference to which it is difficult to attach much significance.

In looking at the dependence of extremely high latitude auroras on the direction of the interplanetary magnetic field another approach is taken, one that appears to have growing success in ordering high latitude magnetospheric data. The cases of auroras are distributed for each category according to the direction of the IMF in the y-z plane. The distribution is made in 10° bins.

Figure 15 shows the distribution for all cases. It is strongly skewed in the $-B_y$, $+B_z$ quadrant as expected from the previous distributions.

Figure 16 shows the four distributions for given P-categories. Here are plotted the percentage of the total number of cases within a given category, instead of the actual number plotted in Figure 15. The number of cases in each category is listed. In comparing categories P(1), P(2) and P(3) there is a definite trend to rotate the major portion of the distribution from positive B_z and negative B_y for morning aurora to positive B_z and positive B_y for evening aurora, with single arcs occurring when the projected B is pointing northward (for small B_y).

Because the hourly averaged values of the components of the magnetic field are often only a rough indicator of the state of the magnetic field we selected the cases of extremely high latitude auroras for which B_y and B_z stayed in the same quadrant for two hours before the DMSP image was made. If the effect of the direction of the IMF in the y-z plane is real, it should be more pronounced for a magnetosphere subjected a longer time to the same condition. The distributions according to P-category are shown in Figure 17. Again, the percentage of the total is plotted, this time for each 30° interval in the direction of B projected on the y-z plane. The number of cases in each category is listed. The bin size is increased because the sample size is so greatly reduced. The distributions show the same trend found above: extremely high latitude auroras tend to occur in local time preferentially with the direction of the interplanetary magnetic field in the y-z plane. Assuming B_z positive, they occur in the morning for B_y negative (or for toward sectors) and in evening for B_y positive (away sectors).

In examining the occurrence of cap auroras in relation to other wind parameters: n, the number density; v, the solar wind velocity; B, the magnitude of the interplanetary magnetic field; and T, the temperature; only correlation with v appeared to have obvious significance. Figures 18 and 19 show the number of cases of extremely high latitude auroras distributed according to solar wind velocity. Figure 18 is the distribution for all cases. Figure 19 shows the distribution for each P-category. The dashed line shows the distribution for daily averages for the month of December, 1974, normalized to the same number of cap cases. The monthly distribution is similar to that shown by Gosling et al. (1976) for the solar wind in 1974, with well-developed high speed streams. This distribution has a fairly flat peak for velocities between 400 and 600 km/sec. In 1972, the two stream wind had not yet developed and the most probable value of the velocity was around 400 km/sec. The distribution for extremely high latitude auroras has a most probable value between 650 and 700 km/sec, a significant increase over the normal occurrence distributions.

When distributed according to P-category the shift to high solar wind velocities remains except, perhaps, for single arcs: Category P(1). In fact, all distributions appear to be made up of two parts: a low velocity distribution centered about 450-500 km/sec and falling rapidly to either side; and a high velocity distribution with most probable value between 650-700 km/sec. Such a combination would give the rather strange dearth of cases between 500-600 km/sec. The low velocity distribution is not unlike the normal (slow stream) solar wind velocity distribution and the inflation in the distribution for cap auroras could simply be a reflection of the fact that such values occur much more often. If this is the case we can conclude that extremely high latitude auroras are much more likely to occur when the solar wind velocity is high.

For the midnight oval expansions, P(4), the distribution in low solar wind values is almost entirely missing; 87% of the cases occur for solar wind velocities greater than 550 km/sec. The next most convincing distribution for high latitude occurrence at high solar wind velocities is for morning auroras, P(2), where 74% of the cases occur for velocities greater than 550 km/sec.

The distributions for single arcs and evening arcs are nearly the same for the high velocity and low velocity values. Still the number of high velocity cases is substantial.

Distributions for all cases of extremely high latitude auroras with other solar wind parameters are shown in Figure 20. The density and magnetic field magnitude distributions are quite similar to those found overall in the solar wind. The temperature, too, while having a major part of the distribution for larger temperatures than normal on the whole, is at values expected for high velocity streams (Feldman et al., 1976).

To more clearly show the rather striking dependence of the occurrence of cap auroras and solar wind velocity a summary of occurrence of cap auroras and the variation of several parameters for November, 1974 is shown in Figure 21. In the first panel the unshaded histogram gives the number of DMSP images on a given day on which the correct latitudes and the proper gains appear so that polar cap arcs could be seen if they were above the radiometer threshold. The brightness of the full moon at the end of the month obscures all auroras. The shaded histogram gives the number of DMSP images that do show extremely high latitude auroras in categories P(1) to P(3). The percentage of cases that occur for the number possible is given in the second panel. The third panel shows magnetic activity as measured by the sum of K_p (solid line), the

daily average of AE (dashed line) and the daily average of D_{st} (negative values). Finally, the fifth panel shows the daily average of the solar wind velocity. There is rather remarkable similarity between panels 2 and 4.

In retrospect, choosing DMSP images from winter 1974-75 to study polar cap auroras may have been particularly fortuitous since it is also the time of uncharacteristic high speed stream structures in the solar wind. The DMSP images for this time have excellent quality and coverage. Often in image after image arcs appear at latitudes greater than 80^{o}, creating the impression of very high frequency of occurrence. Such high frequency does not seem to be characteristic of the Winter 1972-73. In addition, it has not been as easy to find examples in more recent DMSP images as one would ascertain from the 1974-75 data base.

Discussion

To this point we have avoided discussion of how the occurrence of extremely high latitude auroras do or do not fit into various magnetospheric models. The data are presented in this austere manner to stress the variety of circumstances under which the polar cap becomes significantly involved in magnetospheric dynamics. Putting the case somewhat differently: using the results presented above an effort was made to predict from magnetic activity and solar wind conditions when auroral arcs would be present in the cap regions. The results were unimpressive. Even more perplexing were case studies of successive passes such as those presented in Figure 1 to 3. It was not difficult to find examples of auroral activity maintained in the polar cap regions for time periods of many hours. (Refer also to Figure 21.) No system of changes that could apply from case study to case study was apparent. Indeed, it often seemed that just the opposite of what one might expect actually occurs. Case studies can leave

the impression that auroral arcs may occur at extremely high latitudes under almost any set of ground magnetic and solar wind conditions as specified by hourly averages, an impression which is reflected in the large scatter found in all quantities correlated with occurrence.

A second caution applies to the data. When the survey of all DMSP images was made it was assumed that the Winters of 1972-73 and 1974-75 were the best choices because of the quality of the DMSP images: that they were more consistently in proper gain states for detecting polar cap arcs. In the sample discussed here more than 80% of the images were obtained during the winter of 1974-75: the peak period for stable, recurrent high speed streams in the solar wind, (Gosling et al., 1976). Holzer and Slavin (1979) show that the efficiency with which energy is transferred from the solar wind to the magnetosphere is much greater (about 50% greater) for high speed streams than for normal speeds. They also suggest that the morphology of the interplanetary magnetic field in the high speed streams may also differ greatly from the normal case. Thus, the period from which the data in this study are extracted may be atypical having much more favorable conditions for producing extremely high latitude auroras than is otherwise the case. With these two points in mind we consider the results.

One category of extremely high latitude auroras is distinctly different from the rest: the oval auroras that expand poleward in the midnight sector, those in Category P(4). These occur for conditions that are characteristic of substorms: moderate to high K_p and AE; B_z southward and v large. Dependence, if any, on B_y is obscure. At this point it is not possible to determine the relationship of this class of active auroras to the entire spectrum of substorm

events. It is quite clear, however, that the poleward boundary of the oval can have very large fluctuations even in the midnight sector and for large magnetic activity.

Consider the three remaining categories of extremely high latitude auroras: P(1), P(2), and P(3). All three have maximum occurrence for similar magnetospheric and solar wind conditions. These are:

a. the interplanetary magnetic field has a northward component;

b. the solar wind speed is high;

c. moderate mid-latitude magnetic activity, as measured by K_p;

d. low auroral zone magnetic activity as measured by AE.

In addition, they preferentially occur in the cap according to the direction of the interplanetary field in the y-z plane.

Taken individually we find good agreement with previous studies in conditions a) and d). Berkey et al. (1976) and Ismail et al. (1977) find that all the cases of sun-aligned polar cap arcs which they selected from the Isis data for study (approximately 50 cases) occur for B_z northward (or undetermined). The criterion used to select cases in the study presented here is more inclusive than theirs and gives a sample similar in more respects to that of Lassen and Danielsen (1978) who show that it is possible for arcs in the morning sector to reach latitudes greater than 80^o for all values of B_z to -7γ, although the mass density plots of the arcs increasingly show greater densities as B_z becomes more positive. We find, as well, that while the great majority of cases of extremely high latitude auroras in the first three categories occur for B_z positive there is a substantial scatter into negative values of B_z, more prevalent for morning arcs (corresponding to the morning arcs of Lassen and Danielsen), but also for P(1) (corresponding to the arcs in the studies of the Isis data) and P(3).

The finding that extremely high latitude auroras in these categories occur principally for low AE is consistent with the generally held notion that occurrence of polar cap auroras anticorrelates with magnetic activity (Davis, 1963, Ismail et al., 1977). The finding that peak occurrence obtains for moderate K_p is not consistent with this notion. Instead of focusing on the specific merits and problems of either index (AE is an indication of auroral zone activity; K_p of subauroral zone or midlatitude activity) or of the use of these in studying polar cap arcs, we suggest a somewhat different conclusion may be drawn from the data presented here: namely, the occurrence of auroral arcs at latitudes greater than 80^o may more accurately be a function of the ratio of K_p to AE, than of the two taken separately.

In a comprehensive study correlating magnetic indices and solar wind parameters (three hour averages) Maezawa (1978) has shown that the ratio of A_m (a subauroral zone magnetic index) to A_L (the nightside auroral zone, or westward electrojet index) increases with the magnitude of B when B_z is northward. Thus, there can be significant transfers of energy from the solar wind to the magnetosphere a) when B_z is northward, and b) without substantially involving the auroral zones. Maezawa suggests overall compression and expansion of the magnetosphere as the mechanism of energy transfer. It would be operable for all values of B_z but apparent only when the auroral zone activity is sufficiently quiet not to obscure the effects of this second mode of interaction, that is, for those times of little substorm activity.

The pertinence of Maezawa's study to this one is twofold. First, it isolates situations of B_z northward and indicates that during such times the ratio of A_m to A_L (read K_p to AE) may be an appropriate measure of the state of the magnetosphere, systematically changing with at least one solar wind

parameter - the magnitude of the interplanetary magnetic field. Second, it does not exclude the possibility that transfers of energy to the magnetosphere by the mechanism that increases the ratio of A_m to A_L and identifiable during times of B_z northward, may also occur for B_z southward. Our study shows that extremely high latitude auroras in Categories P(1)-P(3) are most likely not substorm related. But it also shows that they do not occur when there is little or no magnetic activity. That is, there must be an energy transfer to the magnetosphere to cause auroral phenomena at extremely high latitudes, but it need not involve the auroral zones. Involvement of the extremely high latitude regions simultaneous with involvement of the auroral zones is not excluded (as may be indicated by the scatter of occurrence of extremely high latitude auroras into negative B_z values), although the transfer of energy to one region may be more efficient when it excludes the other (as indicated by much greater occurrence of extremely high latitude auroras when B_z is positive). Anti-correlation of extremely high latitude auroras with magnetic activity (undifferentiated) appears to be too simple a specification for the occurrence of arcs in the polar cap.

At this point we must reconsider a problem alluded to earlier: the state of the magnetosphere and the involvement of the polar caps under extremely quiet conditions. Extremely quiet conditions will be loosely defined as times for which both K_p and AE are low and remain low for periods on the order of hours. For such times the occurrence of extremely high latitude auroras, found in this study, is low. Figure 21 shows that on November 18, 1974, both ΣK_p and AE_{av} had reasonably low values, but no extremely high latitude auroras were observed. Characteristically, the DMSP images record only quiet oval arcs or nothing during such periods. The problem is this: is the magnetosphere at

times of extreme quiet, when presumably B_z is northward steadily for hours, in essentially a different state than other times of B_z northward, characterized in this study by the occurrence of arcs in the polar cap; or are the two states essentially the same and differentiated simply by intensity or the amount of energy transferred to the cap? If the latter were the case, particles (electrons) would precipitate into the cap regions in essentially the same configurations and by means of the same acceleration mechanisms for all B_z north situations. But, for extremely quiet times the energy fluxes would be less and presumably below detectability by the DMSP radiometer. Clearly such a question can only be answered by examination of particle data. Nevertheless, it may be the case, as suggested by the Maezawa study and the results of this study, that a hierarchy of magnetospheric states exists for B_z northward which are as complex and varied as the storm and substorm conditions during B_z southward; and while these states may involve a lesser transfer of energy than for B_z south the mechanisms of transfer may be equally fundamental to a magnetospheric dynamics.

Finally we turn to the question of how solar wind energy transferred to the magnetosphere during times of northward B_z, and transferred particularly to the polar cap regions (and presumably to their extension, the tail lobes), results in arc formation.

Maezawa's (1977) energy transfer to the magnetosphere for positive B_z has little, if any, dependence on the solar wind velocity v. However, we find extremely high latitude auroras occur preferentially for high v. In addition, the position of their occurrence depends on the direction of B in the y-z plane. Therefore, these parameters may relate more directly to the mechanism of energy transfer rather than to the amount of energy transferred.

Two quantities which depend strongly on v and the direction of B are the convection electric field in the solar wind ($\underline{E} = -\underline{v} \times \underline{B}$); and the position and rate of dayside merging. Few comprehensive theories have been developed to relate the convection electric field in the solar wind to the convection electric field in the magnetosphere and, in particular, in the polar magnetosphere at times when B_z is northward.

Electric fields are usually invoked to explain the production of discrete oval arcs. Ismail et al. (1977) find the ratio of spectral lines 5577 Å and 3914 Å in sun-aligned polar cap arcs similar to those in discrete oval arcs. The discrete oval arcs generally occur in regions of reversals of the convection electric fields. The convection electric field at high latitudes may result from viscous interaction of the solar wind and the magnetosphere or by magnetic field merging, or, indeed, by a combination of the two. (See Crooker, 1978, and the references therein.) The electric fields consequent to magnetic merging have generally been treated for a southward directed B_z. Crooker (1979) used open field line merging during times of northward B_z along with viscous interaction on the closed field lines as the source of high latitude and polar cap convection electric field patterns. The strength of the field depends on the merging rate and, therefore, on v. The regions of merging (where the interplanetary and magnetospheric fields are anti-parallel) are determined by the direction of B in the y-z plane. For both B_y and B_z positive the convection flow in the north polar cap is antisunward in the morning and the return flow, sunward flow, is in the evening. (The reverse is the case for B_y negative and B_z positive.) The resulting convection electric fields are dawn to dusk in the morning and dusk to dawn in the evening. Maezawa, (1976), finds

evidence of a reversed, dusk to dawn, electric field for northward B_z in ground magnetometer records after the effects of B_y are removed. Burke et al. (1979) have examined polar cap electric fields as measured by S3-2 for times of B_z northward and find both irregular electric fields across the cap (a series of many reversals) and large regions of reversed (dusk to dawn) fields. Combining the predicted B_y dependence of the cap convection patterns with the statistical results presented here we can conclude that extremely high latitude auroras are found to occur preferentially in the region of predicted reverse (sunward) flow, or the region of dusk to dawn electric fields in the cap.

The region of predicted sunward flow, which is the region where arcs occur preferentially for B_z positive and a given B_y is on the opposite side of the cap from:

a) the region of increased electric fields (Heppner, 1972);

b) the region of increased low energy electron fluxes (Meng et al., 1977);

c) the region that maps into the tail lobe in which the plasma mantle is preferentially observed, (Hardy et al., 1979).

All three depend on B_y in the opposite sense that occurrence of extremely high latitude auroras do.

It should, however, be noted that none of the three findings in a), b), or c) differentiate between B_z northward and B_z southward, and there is some evidence that the signatures in all three cases occur more clearly for B_z negative. Burke et al. (1979) found more cases of irregular electric fields across the cap during times of B_z northward. These would not have been included in the study of B_y dependence made by Heppner (1972). No information on B_z is presented in the study by Meng et al. (1977) with the exception that the one case study

shown, which lasted over several hours, occurred for a southward B_z. And it was noted by Hardy et al. (1979) that streaming plasma reaches lunar distance, where the study was made, more frequently for B_z southward.

The point is this: the three quantities increasing together on one side of the magnetosphere form a coherent picture. An increased dawn to dusk electric field increases convection of dayside magnetosheath and cusp particles into the same side of the magnetosphere, thereby "filling" it with particles. The low energy electrons precipitate into the caps; the more energetic protons continue streaming anti-sunward while expanding into the tail lobes.

What is required for auroral arcs in the polar cap is quite a different set of circumstances. We need an electron population above the caps asymmetric in B_y in the opposite sense described above. (It is possible that there are always enough particles in the tail lobes to fulfill requirements for arcs thinly distributed over the large spatial extent of the cap. But the point will not be argued further.) More importantly an acceleration mechanism is required that will produce arcs similar to those in the auroral oval. It must be highly spatially structured and capable of lasting more or less constantly for hours. If discrete arcs and reversals of the convection electric field occur together then regular increases in the convection electric field would not produce arcs. More appropriate to arc formation in the caps would be irregular convection fields which are highly spatially structured. Therefore, it is quite likely that the conditions for extremly high latitude auroras are not as orderable as are mechanisms that produce more smoothly varying parameters in the polar caps. The orderability of phenomena in the cap may be much greater for a southward B_z. Or there may be a variety of states for B_z north, only some of which can respond to B_y to give increases in the convection electric

field, low energy precipitating electrons and the plasma mantle as described above. These questions remain to be investigated.

Finally one additional characteristic of extremely high latitude auroras should be mentioned. The three categories P(1), P(2), P(3) are also differentiated by the far more frequent occurrence of morning auroras, P(2), than single arcs, P(1), or evening arcs, P(3). This fact has been mentioned in nearly every study of polar cap arcs, but the substantial dawn-dusk asymmetry it implies for auroral morphology has never been comprehensively treated. The study of Lassen and Danielsen (1978) is the closest to such a treatment. The oval in the morning sector much more readily expands poleward than in the evening sector.

Summary

The polar caps are the extremely high latitude regions of the near-Earth-magnetosphere. They are most clearly differentiated from the surrounding regions, the auroral zones, when quantities such as precipitating particles, electric fields and magnetic fields, have comparatively low values and small variations. The magnetic field lines terminating (or originating) in the cap are swept back from the Earth to form the high latitude lobes of the tail. The field lines in the lobe generally remain open, but may close when the magnitude of the magnetic field is very small. The field lines connecting to the polar caps, being open, can act only weakly, if at all, to store the particles responsible for auroral arcs. In addition, the high latitude tail lobes are 'protected' from solar wind variations since they are surrounded by, but not themselves in magnetospheric boundary regions. The polar cap regions should be regions where not a great deal happens; and most often that appears to be the case.

We have presented here a statistical study of those situations in which the polar caps are not quiet and uniform, but are invaded by accelerated, precipitating particles in quantities sufficient to produce auroral arcs. The involvement of the cap (only arcs in the north polar cap were studied) is greatest at times of B_z northward, and at times when the magnetic activity as measured on the ground derives from other than oval activity. The involvement of the cap can last for several hours and it is also sensitive to the sign of B_y.

The existence of stable arcs at such high latitudes indicates either a significant change in magnetospheric configuration, or in the dynamics of particle motion, or both. This raises the further question of how conditions that lead to arcs in the cap relate to other conditions of B_z north. It is also unclear what characterizes the electric field configurations, the particle entry mechanisms from the magnetosheath and the magnetospheric current systems during these times.

In particular, cases of extreme magnetospheric quiet need to be investigated in relation to times of quiet oval aurora with arcs in the polar cap to determine whether the two states are essentially different from one another or represent the chronology of a single process of decay into a state of magnetospheric quiet.

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Figure Captions

Figure 1. Traces of successive DMSP images showing the development of extremely high latitude auroras into the morning sector on November 11, 1974. The dashed lines are at constant corrected geomagnetic latitudes of 70^{o} and 80^{o}. The solid lines indicate geomagnetic local times of noon-midnight and 06-18. The left-hand column are traces from the noon-midnight Satellite #31; the right from the dawn-dusk Satellite #32. A and A' show no extremely high latitude auroras. B-C' show development of auroras into the morning cap at latitudes greater than 80^{o}. D and D' show a "polar cap" arc.

Figure 2. The format is the same as in Figure 1. Extremely high latitude auroras on November 15, 1974, are shown occurring both in the morning and in the evening sectors.

Figure 3. The format is the same as in Figure 1. Extremely high latitude auroras on November 22, 1974, and November 13, 1974, are shown occurring in the midnight and in the morning sectors.

Figure 4. The number of cases of each type of extremely high latitude aurora (for definition, see text) in the ~300 cases found in Winters 1972-1973, 1974-1975, recorded on DMSP images.

Figure 5. The distribution of all cases of extremely high latitude auroras according to K_p.

Figure 6. The distribution of extremely high latitude auroras, by category (see text), according to K_p.

Figure 7. The distribution of all cases of extremely high latitude auroras according to AE in 50γ bins (solid line). The dashed line shows

the distribution of hourly averages of AE in 50γ bins for November, 1974 when the number of hours is normalized to the number of cases of auroras.

Figure 8. The distribution of extremely high latitude auroras, by category (see text), according to AE.

Figure 9. The relationship of AE and K_p for extremely high latitude auroras, by category.

Figure 10. The distribution of all cases of extremely high latitude auroras according to D_{st} in 10γ bins (solid line). The dashed line shows the distribution of hourly averages of D_{st} in 10γ bins for November, 1974 when the number of hours is normalized to the number of cases of auroras.

Figure 11. The distribution of extremely high latitude auroras, by category, according to D_{st}.

Figure 12. The distribution of extremely high latitude auroras according to the z-component (in solar magnetospheric coordinates) of the interplanetary magnetic field in 1γ bins.

Figure 13. The distribution of extremely high latitude auroras, by category, according to B_z.

Figure 14. The distribution of extremely high latitude auroras according to components (in solar magnetospheric coordinates) of the interplanetary magnetic field in 1γ bins. The top panel is the x-component; the bottom the y-component. The dashed lines give half weight to cases in toward sectors.

Figure 15. The distribution of all cases of extremely high latitude auroras according to the direction of the interplanetary magnetic field in the y-z plane. The bin width is 10°.

Figure 16. The distribution of extremely high latitude auroras by category according to the direction of the interplanetary magnetic field in the y-z plane. The percentage of the total in each category is plotted in bin widths of 10°.

Figure 17. Same as Figure 16 except that the cases of extremely high latitude auroras chosen for these plots occurred during times when the IMF was in the same quadrant in the y-z plane for the two hour period prior to the occurrence of auroras (as determined by the hourly averaged values).

Figure 18. The distribution of all cases of extremely high latitude auroras according to the solar wind speed (solid line). The dashed line shows the distribution of daily averages for December, 1974, normalized to the number of cases of auroras.

Figure 19. The distribution of extremely high latitude auroras, by category, according to the solar wind speed.

Figure 20. The distributions of all cases of extremely high latitude auroras according to the number density, the magnitude of the magnetic field and the temperature of the solar wind.

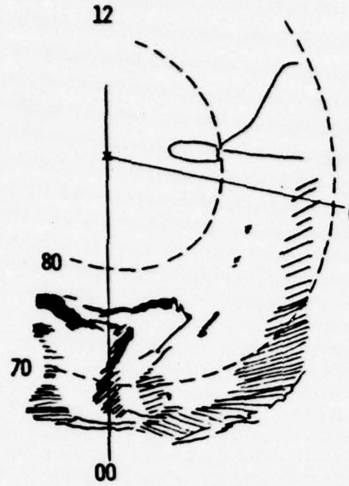
Figure 21. A composite of the occurrence of extremely high latitude auroras and pertinent magnetospheric and solar wind parameters for November, 1974. The top panel shows the number of DMSP images per day that gave good polar cap coverage (unshaded histogram) and the number that showed extremely high latitude auroras in categories 1-3 (shaded histogram). The second panel shows the percentage occurrence of the auroras in categories 1-3 (the ratio of the values in the top panel times 100). The third panel gives the

daily sum of the K_p (unshaded) and the average of the hourly values of AE (shaded). The fourth panel gives the average of the hourly D_{st} values. The fifth gives the average of the hourly solar wind speeds.

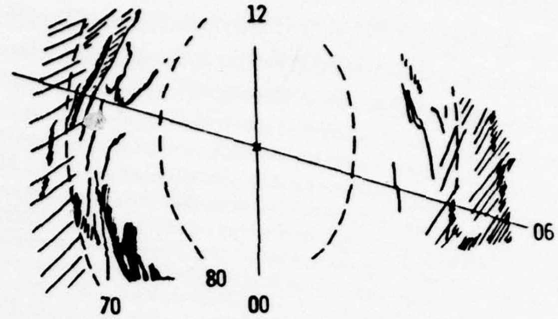
NOVEMBER 11, 1974

SATELLITE # 31
NOON-MIDNIGHT

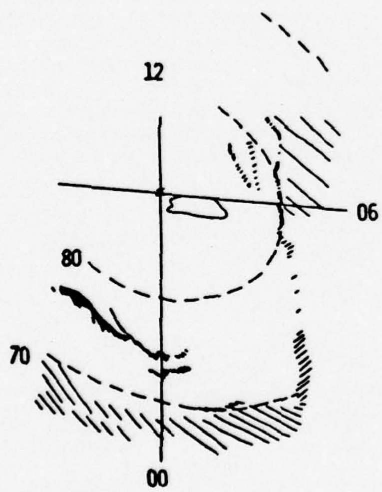
SATELLITE # 32
DAWN-DUSK



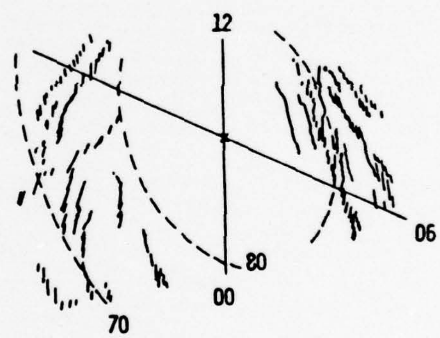
A. 0635UT; K_p= 2; AE = 168.



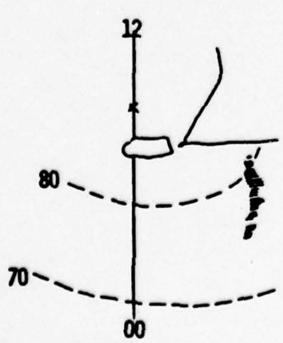
A'. 0646UT; K_p= 2; AE = 168.



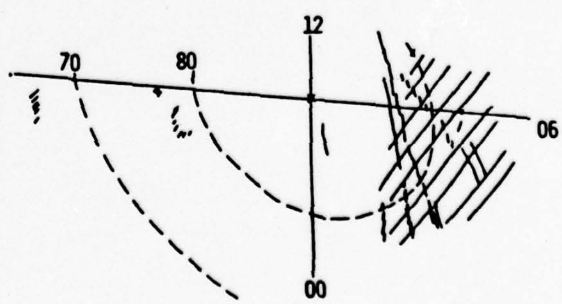
B. 0817UT; K_p= 2; AE = 060.



B'. 0827UT; K_p= 2; AE = 040.

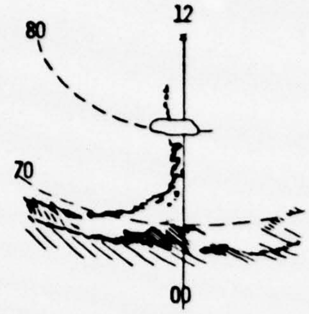


C. 0958UT; K_p= 2+; AE = 036.

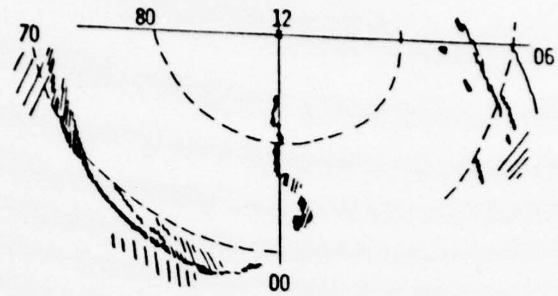


C'. 1009; K_p= 2+; AE = 036.

FIGURE 1



D. 1140UT; K_p = 2+; AE = 218.



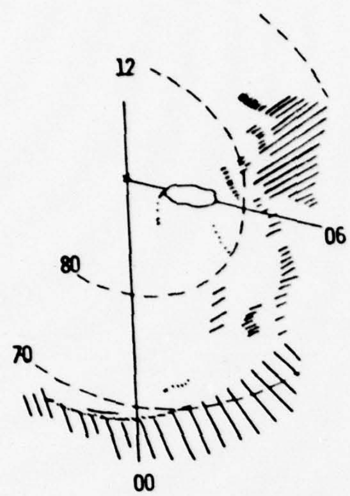
D'. 1151UT; K_p = 2+; AE = 218.

FIGURE 1 (CONTINUED)

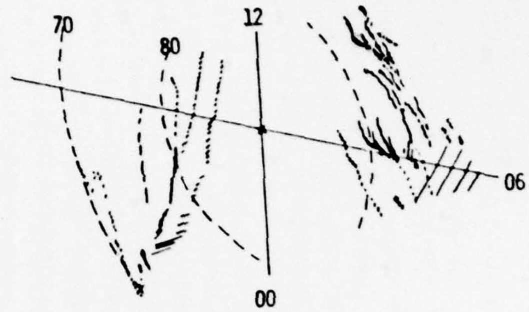
NOVEMBER 15, 1974

SATELLITE # 31
NOON MIDNIGHT

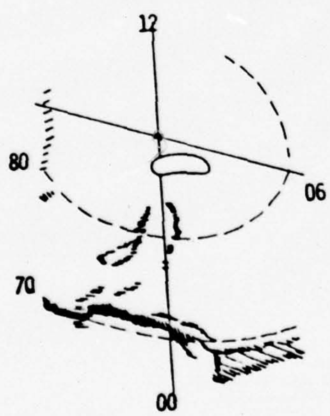
SATELLITE # 32
DAWN-DUSK



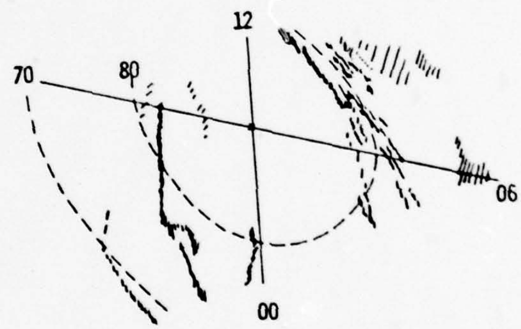
A. 0712UT; K_p= 2-; AE = 103.



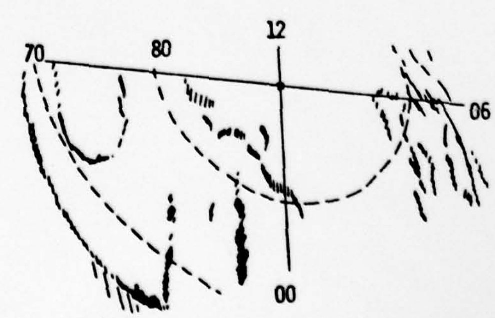
A'. 0716UT; K_p= 2-; AE = 103.



B. 0854UT; K_p= 2-; AE = 048.



B'. 0858UT; K_p= 2-; AE = 048.

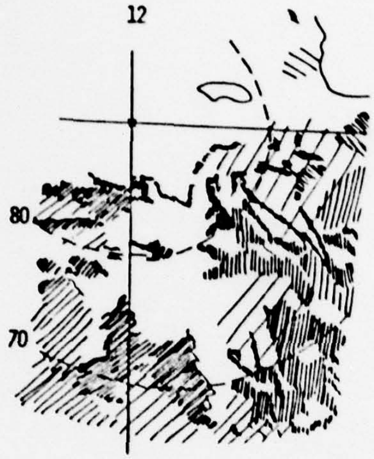


C'. 1040UT; K_p= 3+; AE = 285.

FIGURE 2

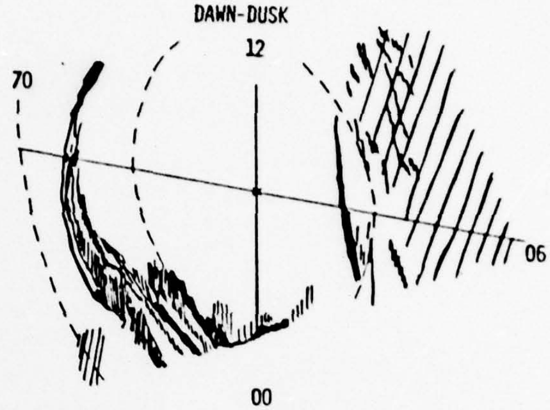
NOVEMBER 22, 1974

SATELLITE # 31
NOON-MIDNIGHT



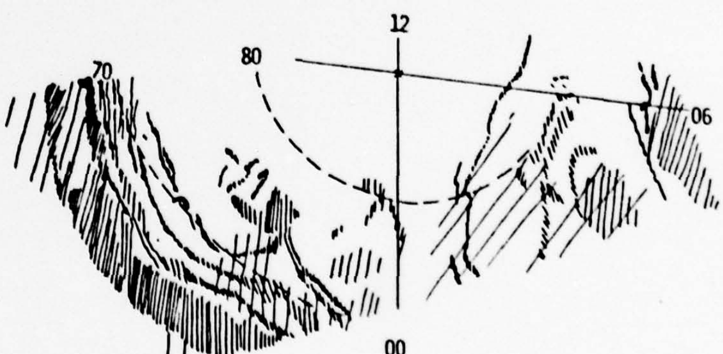
A. 0710UT; K_p = 3+; AE = 342.

SATELLITE # 32
DAWN-DUSK



A'. 0644UT; K_p = 3+; AE = 342.

NOVEMBER 13, 1974



B'. 1111UT; K_p = 5-; AE = 796.

FIGURE 3

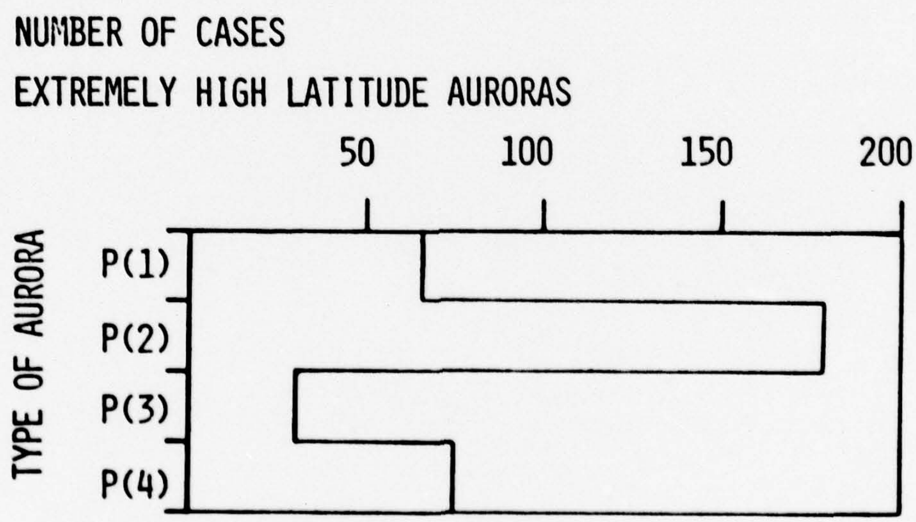

NUMBER OF CASES
EXTREMELY HIGH LATITUDE AURORAS
50
100
150
200
TYPE OF AURORA
P(1)
P(2)
P(3)
P(4)

FIGURE 4

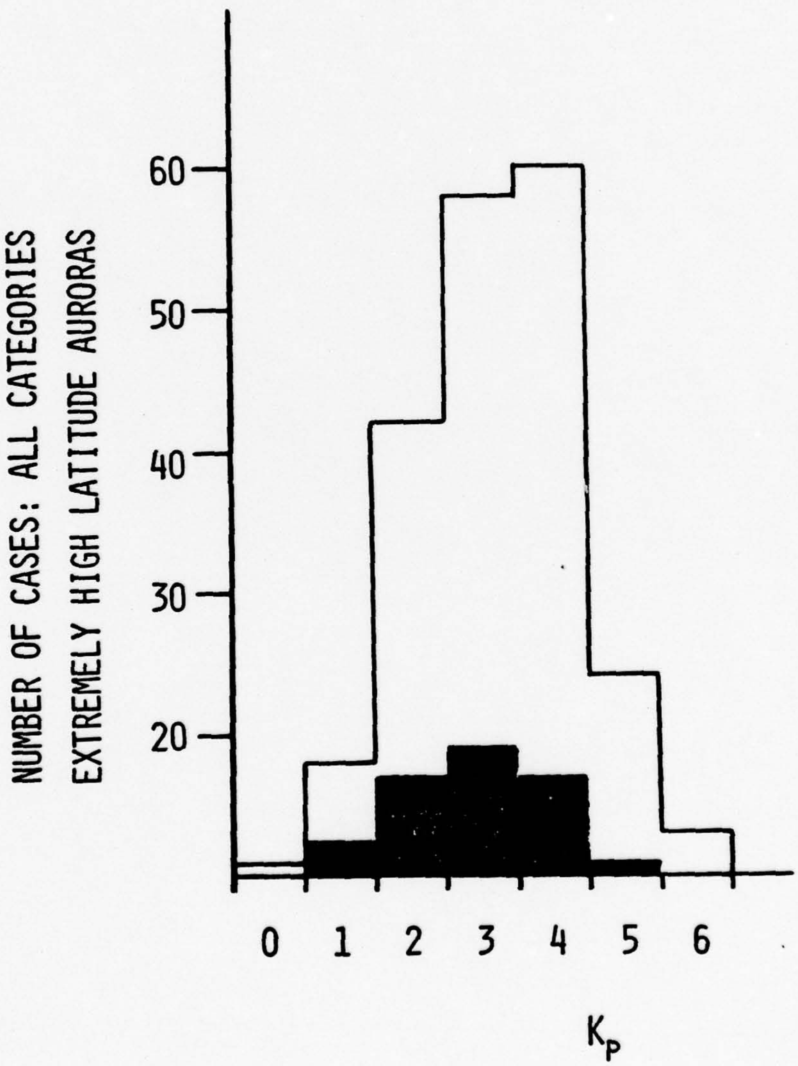

NUMBER OF CASES: ALL CATEGORIES
EXTREMELY HIGH LATITUDE AURORAS
60
50
40
30
20
0
1
2
3
4
5
6
K_P

FIGURE 5

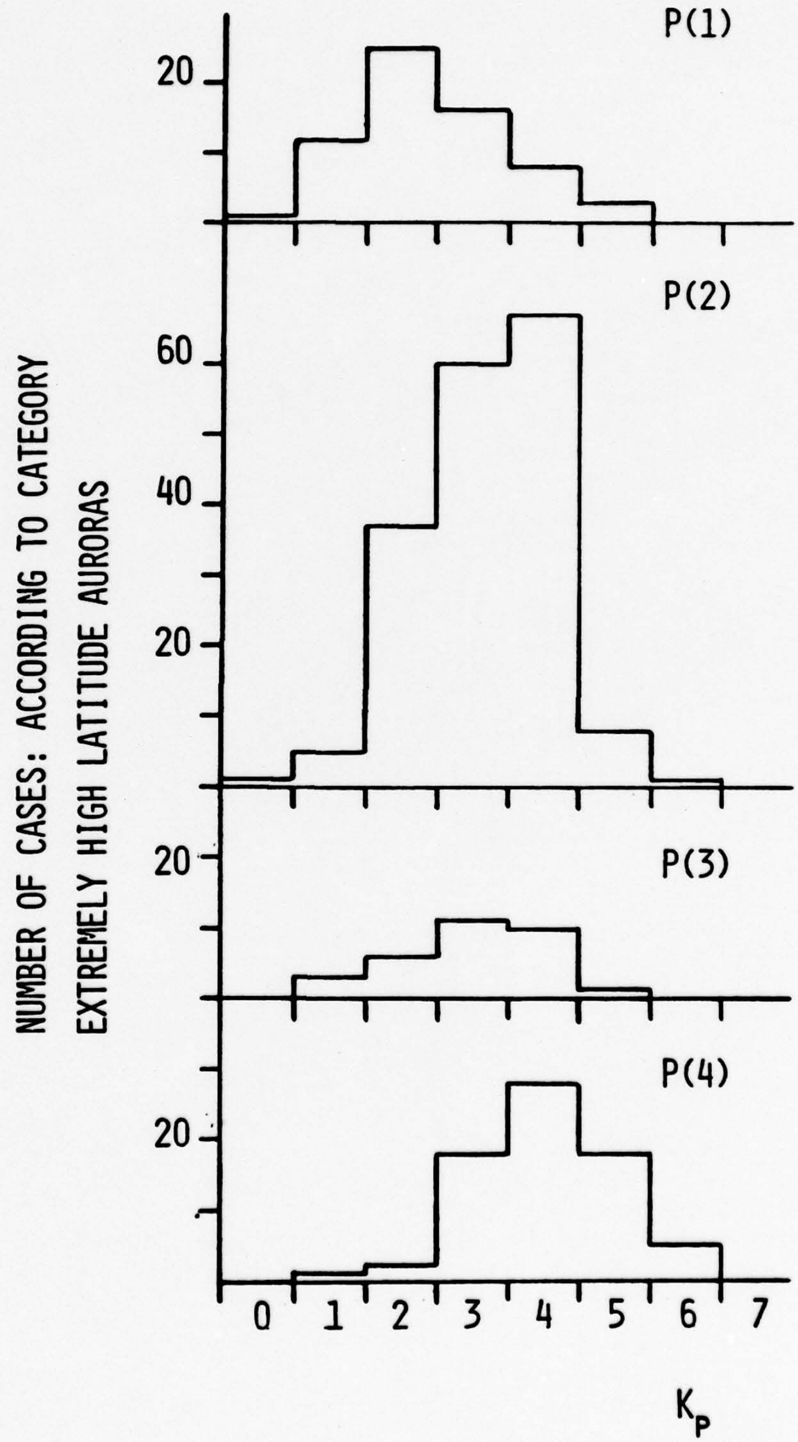
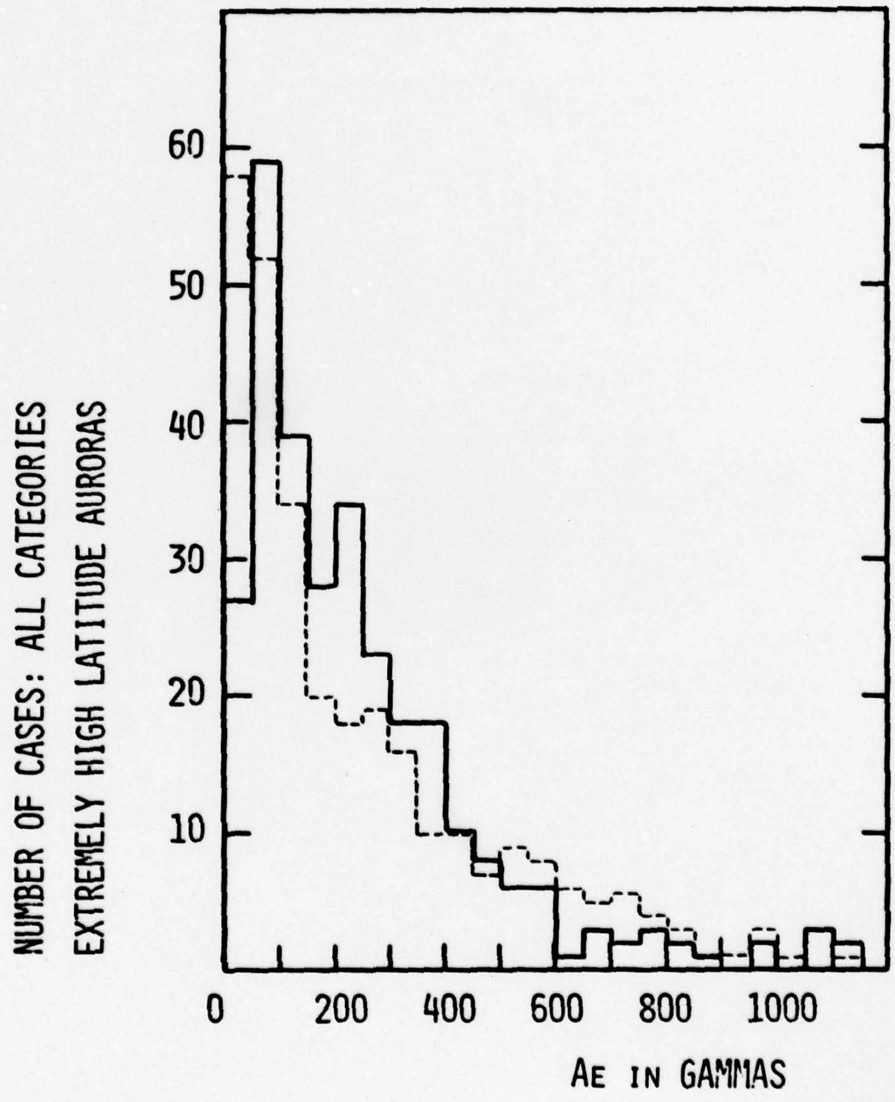

NUMBER OF CASES: ACCORDING TO CATEGORY
EXTREMELY HIGH LATITUDE AURORAS
P(1)
20
P(2)
60
40
20
20
P(3)
P(4)
20
0
1
2
3
4
5
6
7
K_p

FIGURE 6



NUMBER OF CASES: ALL CATEGORIES
EXTREMELY HIGH LATITUDE AURORAS
60
50
40
30
20
10
0
200
400
600
800
1000
AE IN GAMMAS

FIGURE 7

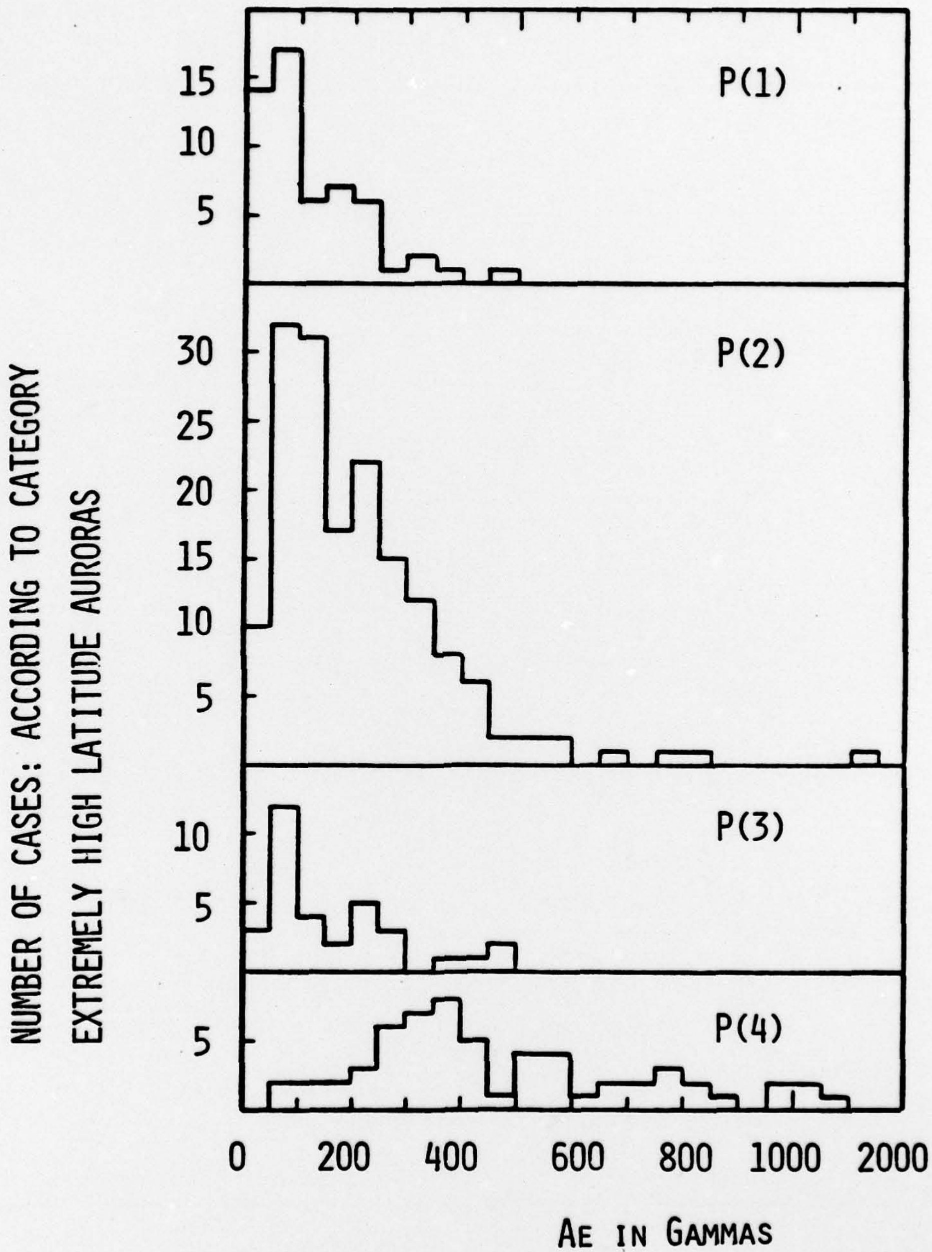

NUMBER OF CASES: ACCORDING TO CATEGORY
EXTREMELY HIGH LATITUDE AURORAS
P(1)
15
10
5
P(2)
30
25
20
15
10
5
P(3)
10
5
P(4)
5
0
200
400
600
800
1000
2000
AE IN GAMMAS

FIGURE 8

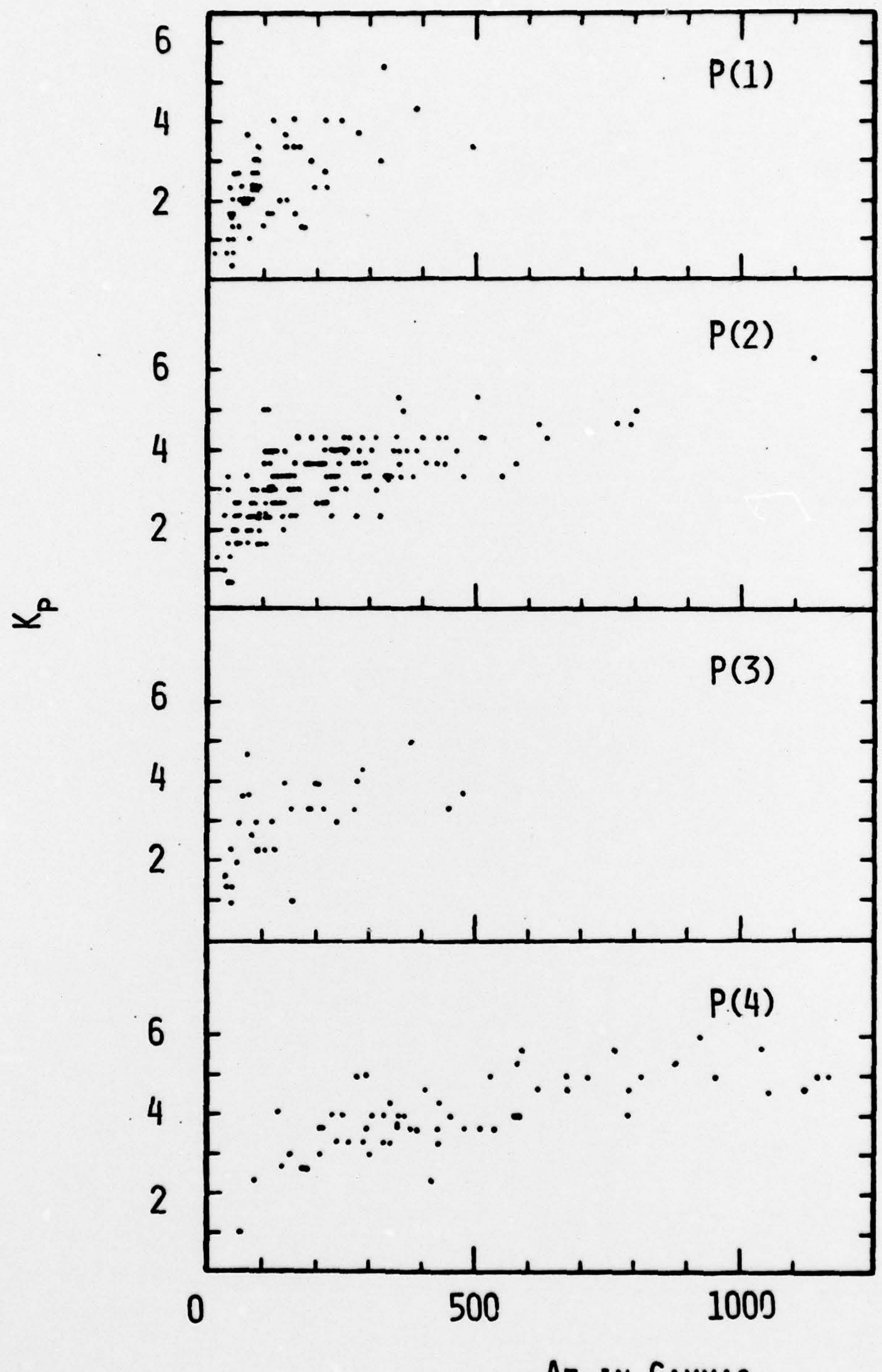
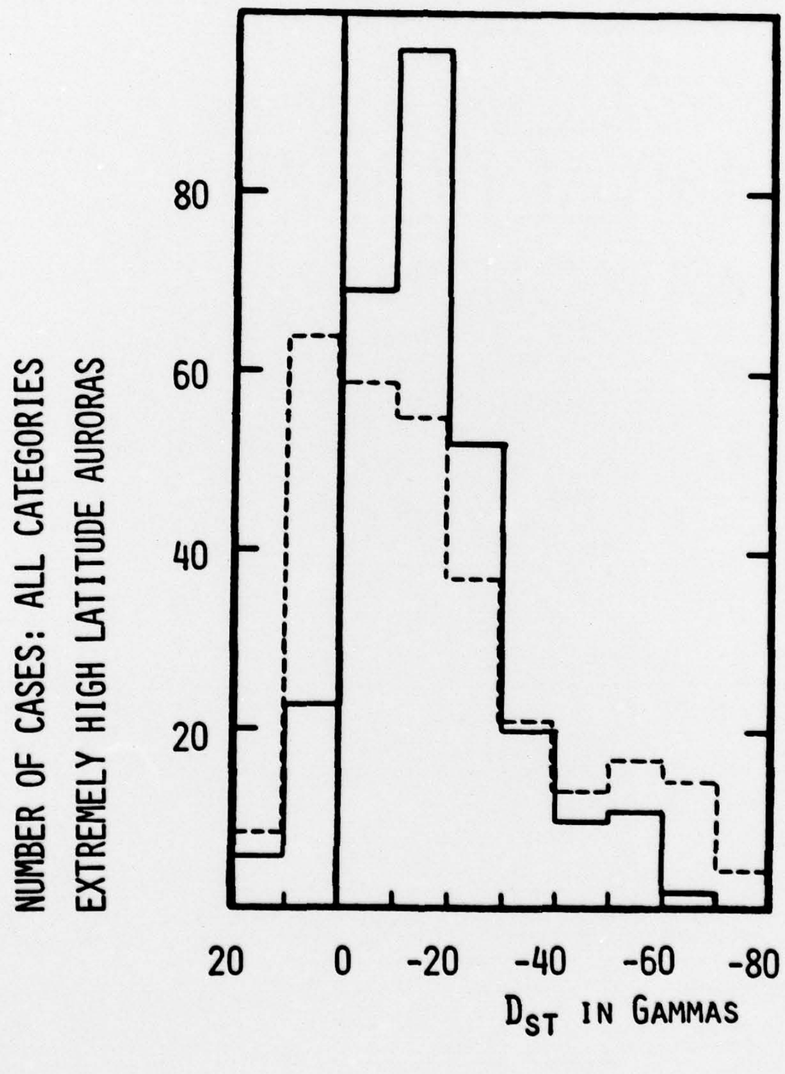


FIGURE 9



NUMBER OF CASES: ALL CATEGORIES
EXTREMELY HIGH LATITUDE AURORAS
80
60
40
20
20
0
-20
-40
-60
-80
D_{ST} IN GAMMAS

FIGURE 10

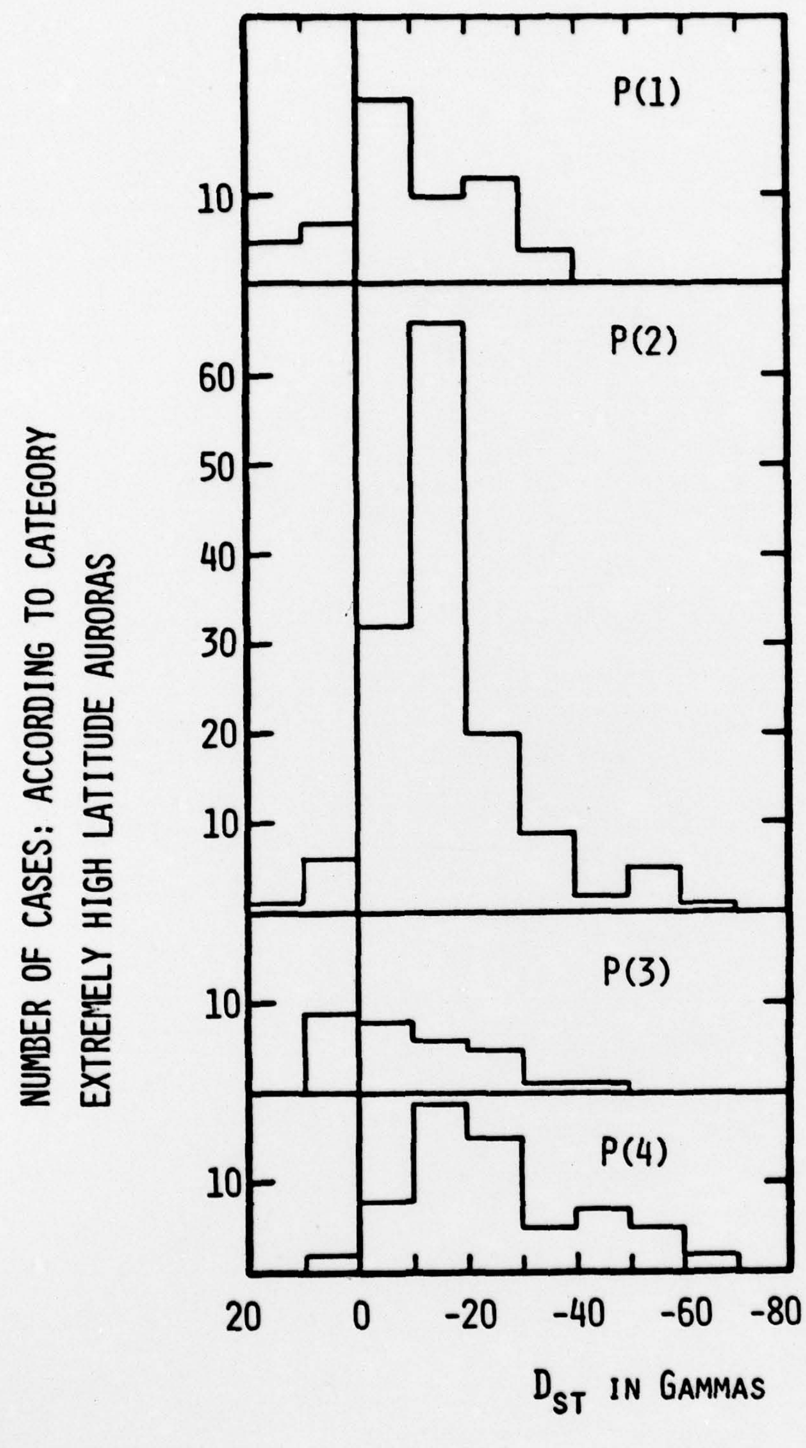

NUMBER OF CASES: ACCORDING TO CATEGORY
EXTREMELY HIGH LATITUDE AURORAS
P(1)
10
P(2)
60
50
40
30
20
10
P(3)
10
P(4)
10
20
0
-20
-40
-60
-80
D_{ST} IN GAMMAS

FIGURE 11

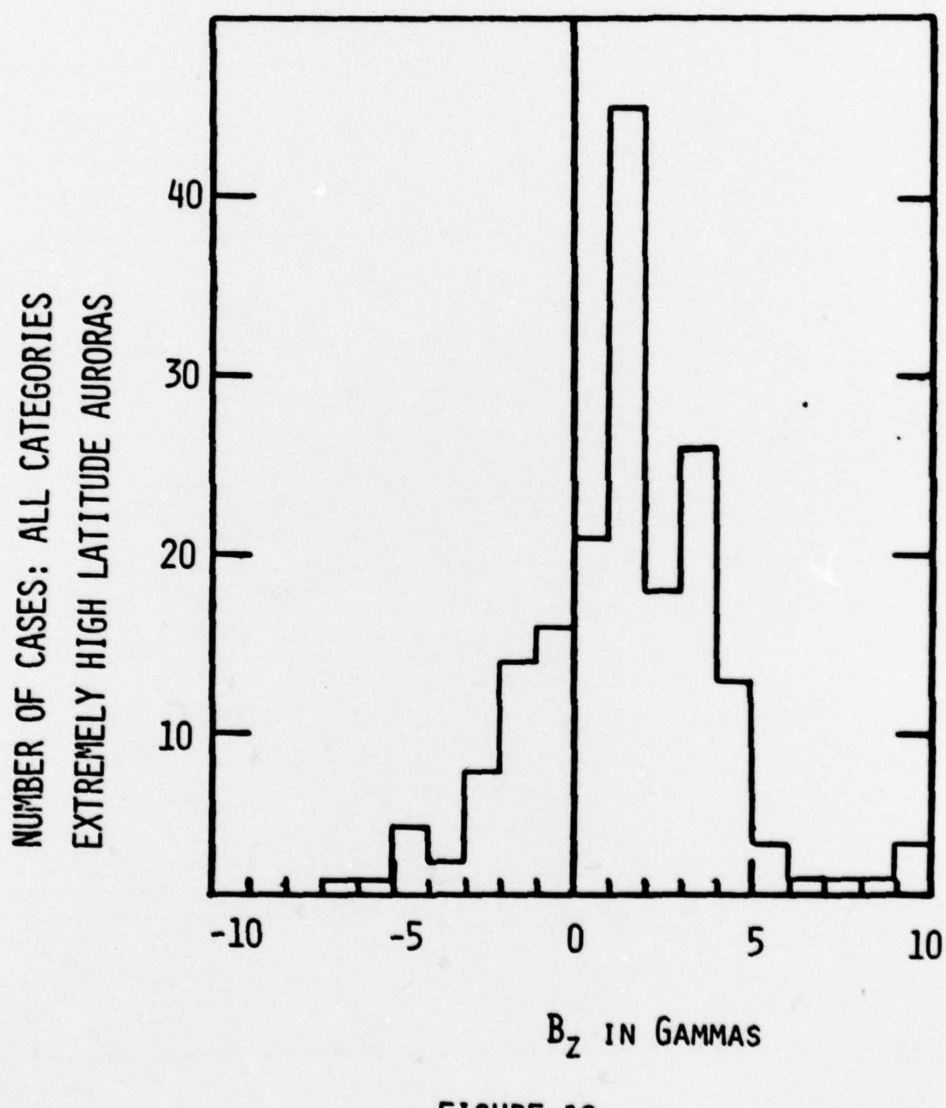

NUMBER OF CASES: ALL CATEGORIES
EXTREMELY HIGH LATITUDE AURORAS
40
30
20
10
-10
-5
0
5
10
B_Z IN GAMMAS

FIGURE 12

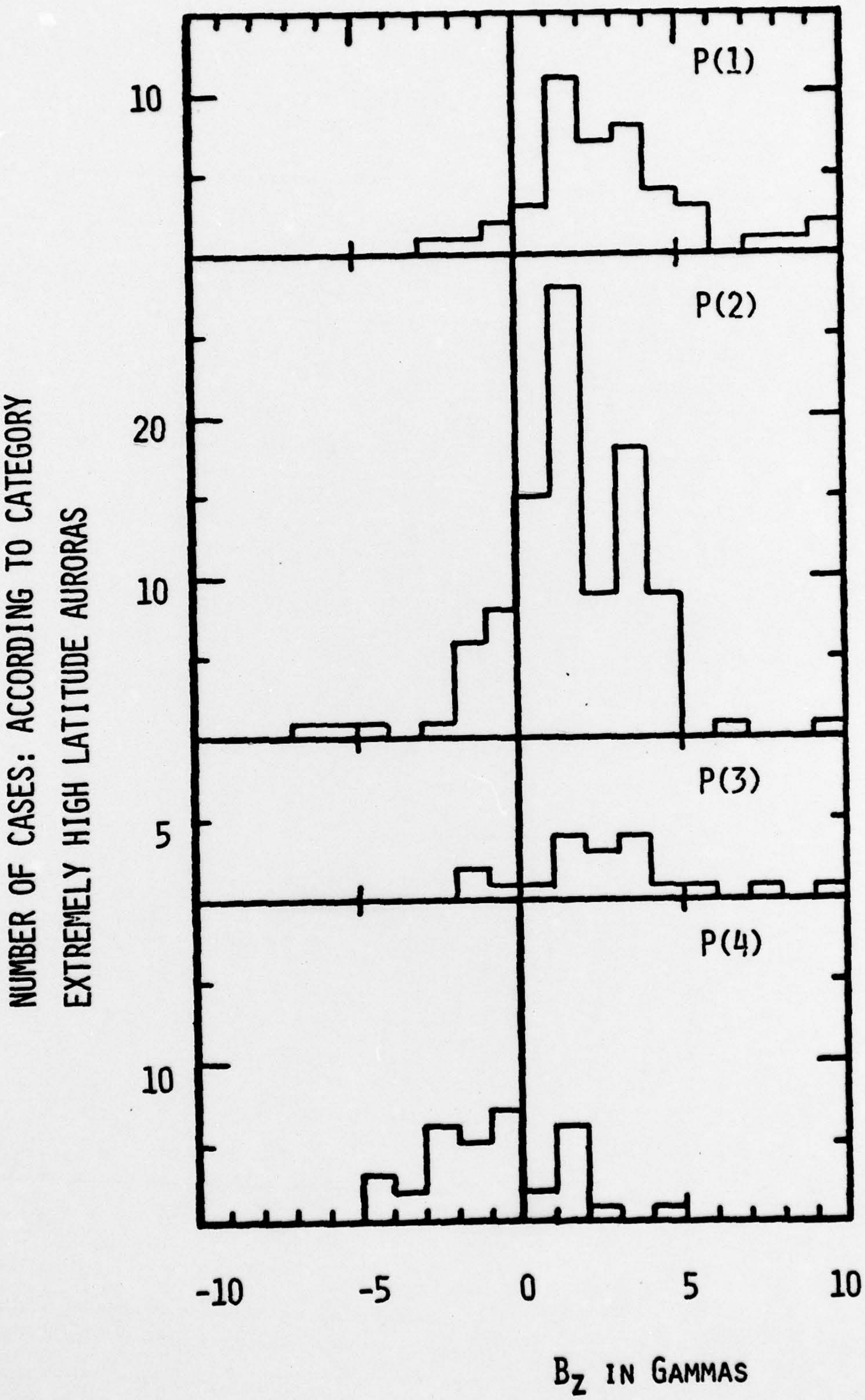

NUMBER OF CASES: ACCORDING TO CATEGORY
EXTREMELY HIGH LATITUDE AURORAS
P(1)
P(2)
P(3)
P(4)
10
20
10
5
10
-10
-5
0
5
10
B_Z IN GAMMAS

FIGURE 13

FIGURE 14

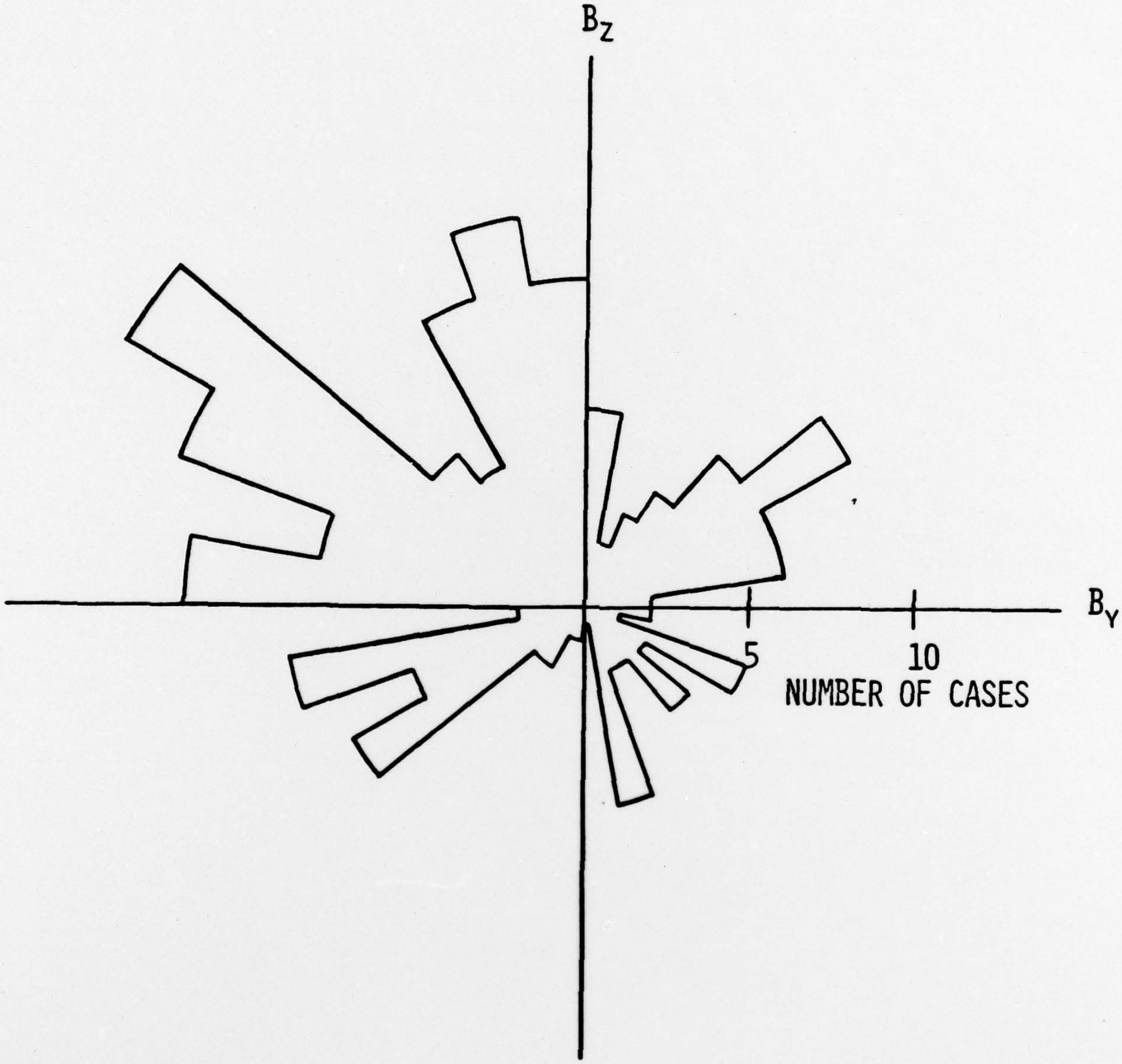
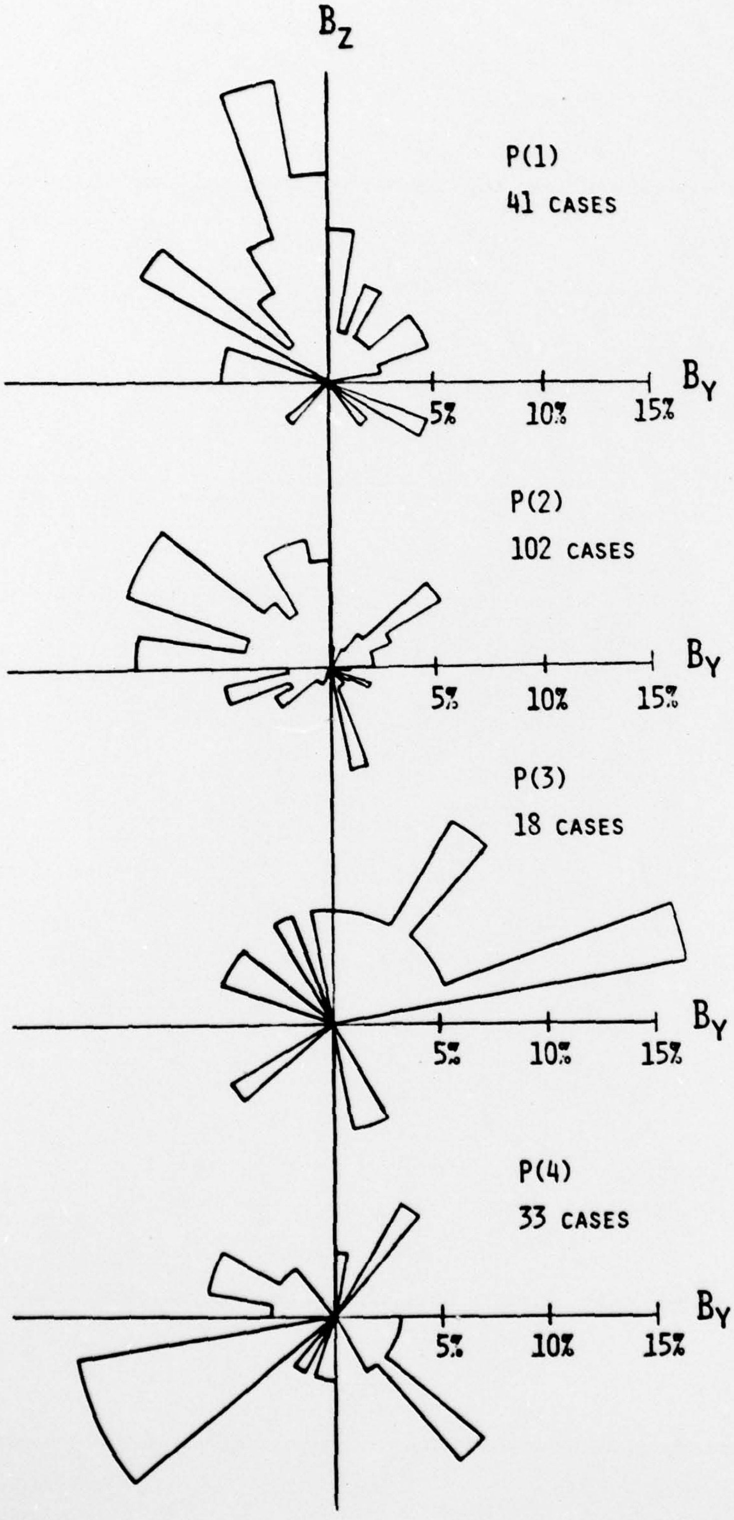
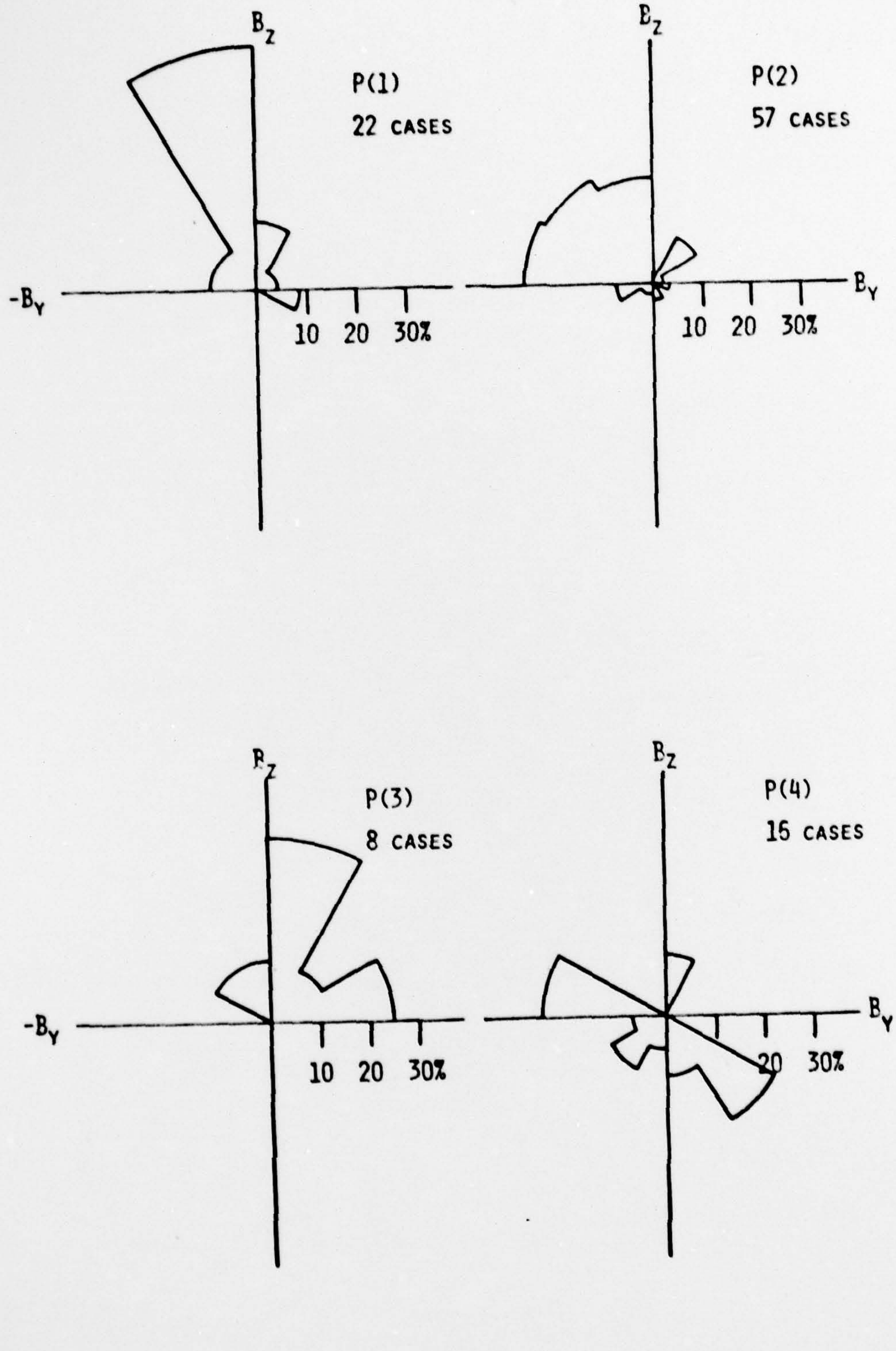


FIGURE 15



B_Z
P(1)
41 CASES
B_Y
5%
10%
15%
P(2)
102 CASES
B_Y
5%
10%
15%
P(3)
18 CASES
B_Y
5%
10%
15%
P(4)
33 CASES
B_Y
5%
10%
15%

FIGURE 16



B_Z
P(1)
22 CASES
$-B_Y$
10 20 30%
B_Z
P(2)
57 CASES
B_Y
10 20 30%
B_Z
P(3)
8 CASES
$-B_Y$
10 20 30%
B_Z
P(4)
16 CASES
B_Y
20 30%

FIGURE 17

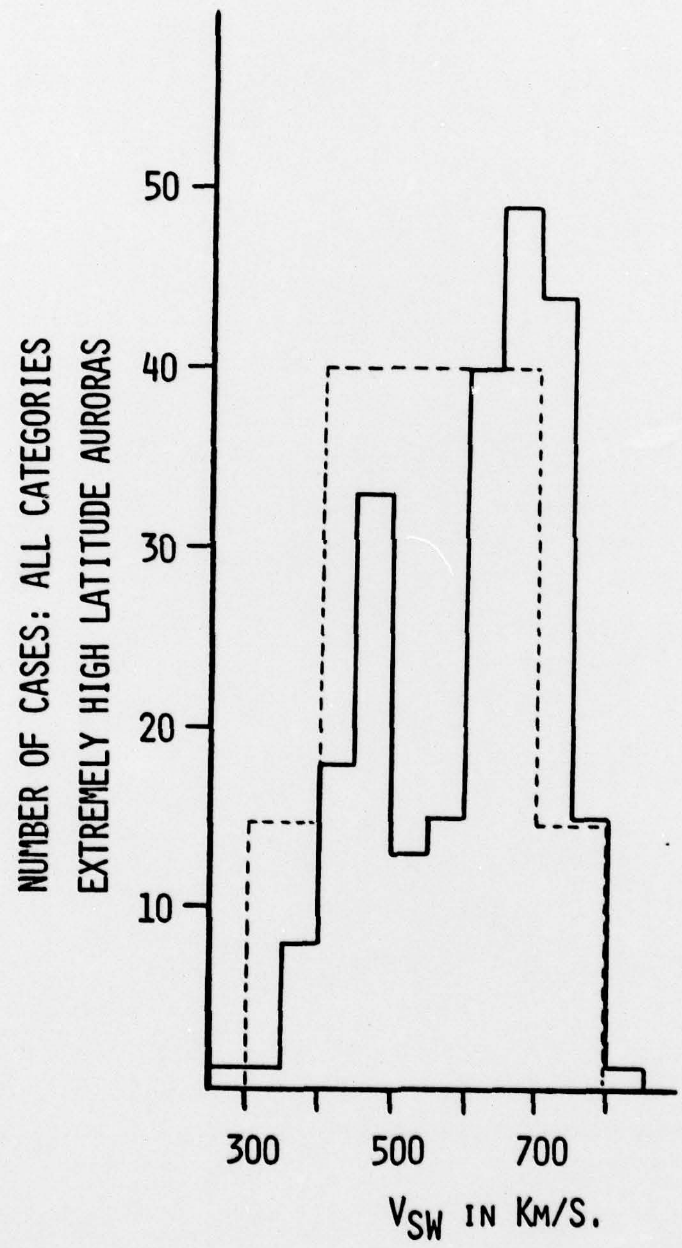

NUMBER OF CASES: ALL CATEGORIES
EXTREMELY HIGH LATITUDE AURORAS
50
40
30
20
10
300
500
700
V_{SW} IN KM/S.

FIGURE 18

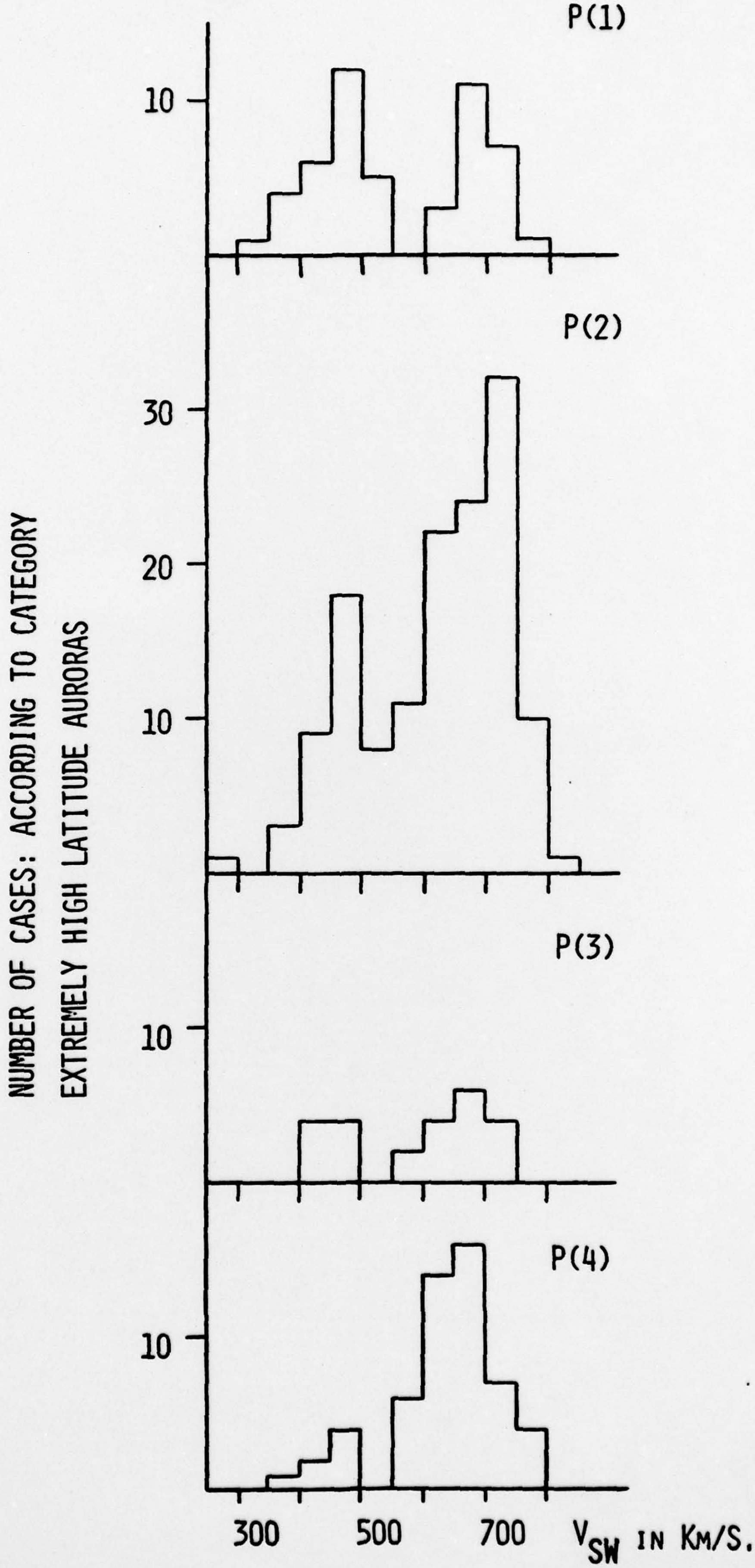
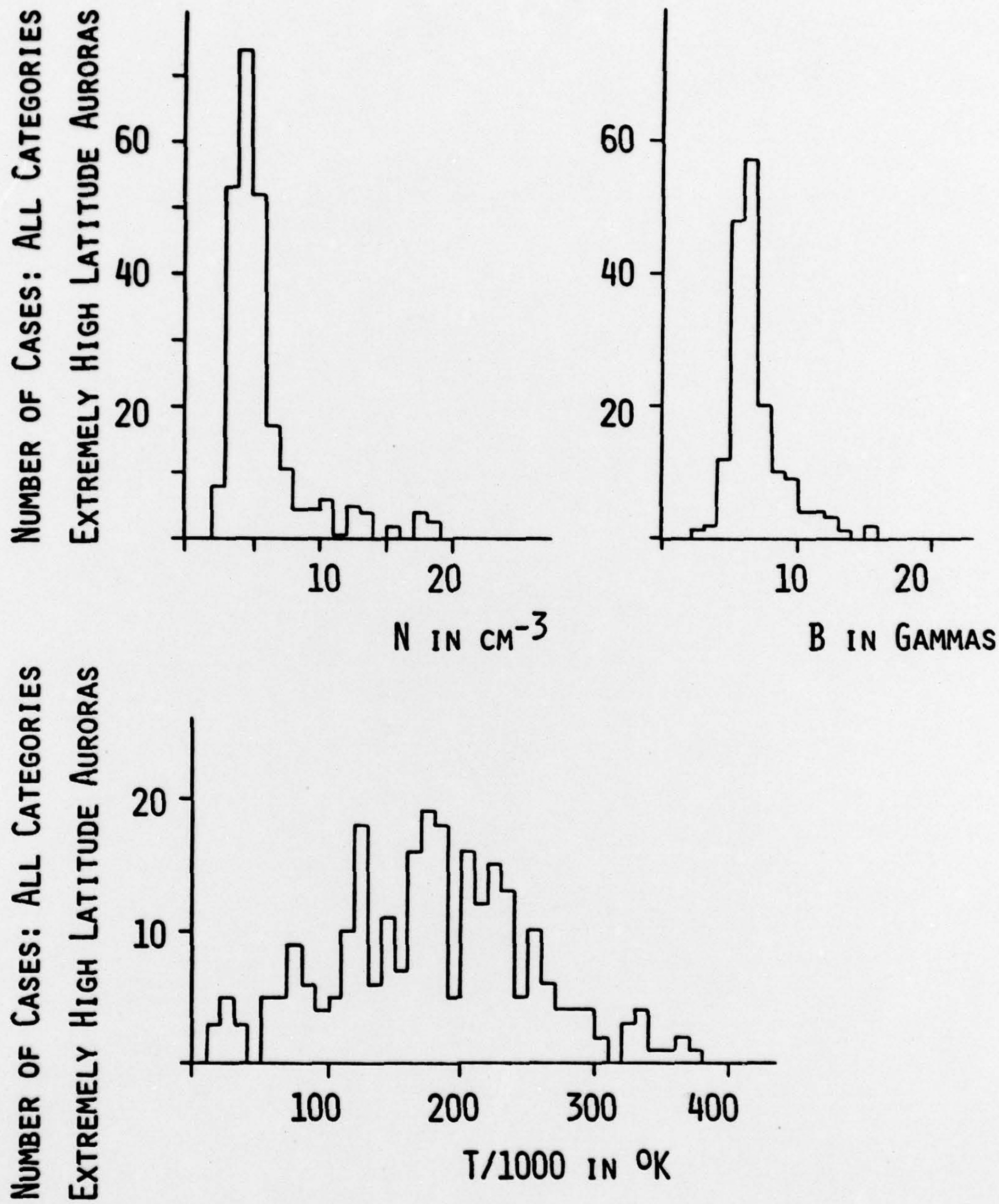

P(1)
P(2)
P(3)
P(4)
10
30
20
10
10
10
NUMBER OF CASES: ACCORDING TO CATEGORY
EXTREMELY HIGH LATITUDE AURORAS
300
500
700
V SW IN KM/S.

FIGURE 19



Number of Cases: All Categories
Extremely High Latitude Auroras
60
40
20
10
20
N in cm-3
60
40
20
10
20
B in Gammas
Number of Cases: All Categories
Extremely High Latitude Auroras
20
10
100
200
300
400
T/1000 in °K

FIGURE 20

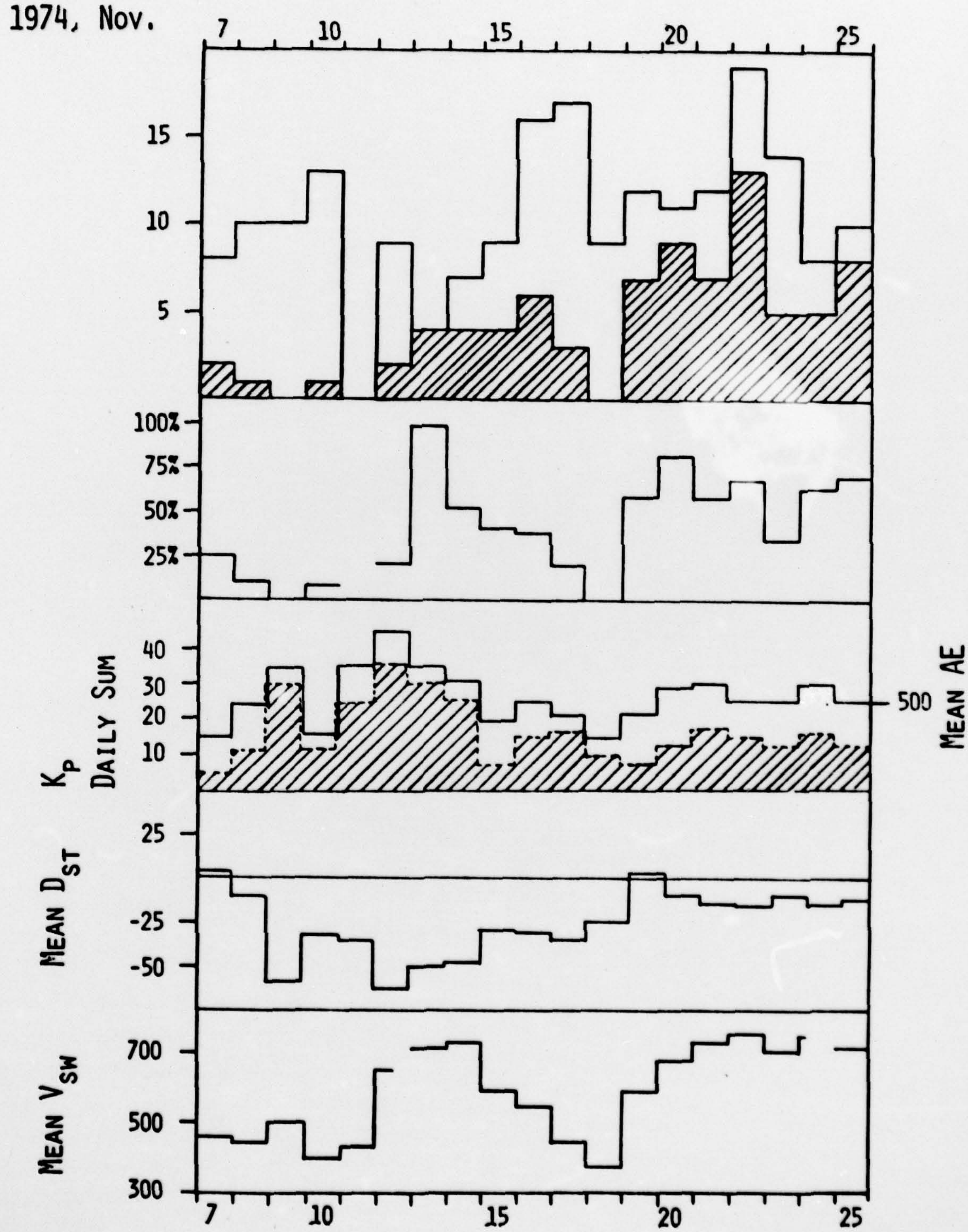

1974, Nov.
7
10
15
20
25
15
10
5
100%
75%
50%
25%
40
30
20
10
K_p
DAILY SUM
500
MEAN AE
25
-25
-50
MEAN D_{ST}
700
500
300
MEAN V_{SW}
7
10
15
20
25

FIGURE 21